The Genetic Variation in Natural and Planted Teak Forests

Characterisation, Use and Conservation for the Future

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The Global Teak Study – Analysis, Evaluation and Future Potential of Teak Resources

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The Global Teak Study

Analysis, Evaluation and Future Potential of Teak Resources

Editors: Walter Kollert, Michael Kleine

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Preface

Teak (*Tectona grandis* L.f.) is one of the most valuable tropical hardwoods of the world. Together with other high-grade hardwoods such as mahogany and rosewood, teak is sought in the global markets for its beauty, strength and stability, natural resistance and wide array of applications ranging from quality furniture through interior joinery to cultural uses. Given the importance of teak, the International Tropical Timber Organization (ITTO), the International Union of Forest Research Organizations (IUFRO) and the Food and Agriculture Organization of the United Nations (FAO) over the past decades have been actively involved in research and development work of natural and planted teak forests. ITTO has been supporting teak related projects with a focus on genetic resources conservation, seed production as well as sustainable management of natural and planted teak forests in Africa, Asia and Latin America. Within its scientific structure, IUFRO maintains a special working party on the "utilization of planted teak" which aims at research and dissemination of scientific information on teak timber produced within the framework of socially and environmentally acceptable norms of sustainable forest management. The work includes identification of superior reproductive material from different provenances in various countries, characterisation and market standardisation of juvenile wood produced in intensively managed plantations as well as developing models for prediction of intensive silvicultural and genetic improvement techniques on timber quality and market end-product value of teak wood. FAO has published two technical reports on teak that serve as a reference on global teak resources and markets in the aftermath of Myanmar's log export ban.

Natural teak forests, in particular old-growth, high-quality stands, are declining. Likewise, the sustained production of teak logs from natural forests is decreasing due to overexploitation of existing stands, deforestation, conversion to other land-uses, and growing competition for environmental services.

In the light of these current threats of deforestation and the constraints in developing sustainable management systems for teak, in 2016 a group of experts from IUFRO, FAO and TEAKNET were tasked by ITTO to organize and implement a global teak study that would address best practices and lessons learnt on the conservation of teak genetic resources and the sustainable management of teak forests in different country contexts in Africa, Asia and Latin America. Towards this end, a retrospective evaluation of the ITTO-supported project "Ex-situ and In-situ Conservation of Teak (*Tectona grandis* L.f.) to Support Sustainable Forest Management" in Myanmar was conducted including a review of other teak-related ITTO projects in Côte d'Ivoire, Ghana, Indonesia, Ecuador and Panama. Guided by these evaluation results a team of IUFRO scientists and other teak experts have synthesised globally available state-of-the-art scientific information and empirical knowledge on teak and have compiled this comprehensive global teak study. The subjects addressed in this report include genetic resources conservation and management; natural teak forest silviculture and stand management; the establishment and management of planted teak forests; wood quality; and economics, production, markets and trade of teak. The report also provides policy recommendations and guidance for future work in promoting sustainable management of natural and planted teak forests in the tropics.

The editors and contributing authors would like to acknowledge the contribution by Ms Margareta Khorchidi and Ms Eva Schimpf (both IUFRO-Headquarters) for language editing as well as financial support by ITTO and FAO to facilitate the production and release of this publication.

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1.1 Introduction

The report "State of the World's Forest Genetic Resources" published by FAO in 2014 lists tree species that are considered national priorities by the reporting countries for the conservation and management of forest genetic resources. Teak (*Tectona grandis*) takes the top rank in this list in more than 20 countries. Economic value (including value of timber, pulp, food, wood energy, and non-wood forest products) is one of the main reasons for nominating the species as a priority for conservation and management.

The international partners IUFRO, FAO, and TEAKNET acknowledge this priority and promote the initiation of a large-scale international research, development and cooperation program. Its goal is to strengthen the conservation and sustainable use of teak genetic resources for the benefit of teak growers, the forest industries, investors and local communities in different country contexts in Africa, Asia/Oceania and Latin America.

The following summary and policy recommendations have been developed and formulated on the occasion of a group meeting of 12 experts[1] from 11 countries that was organised and held by IUFRO and FAO in Vienna, Austria, in December 2016.

1.2 Summary

1.2.1 The Global Situation

Natural teak forests, in particular old-growth high-quality stands are declining. Likewise the sustained production of teak logs from natural forests is decreasing due to overexploitation of existing stands, deforestation, conversion to other land-uses, and growing demand for environmental services from forests. Nevertheless, teak is one of the few emerging valuable hardwood species that has been grown increasingly in planted forests in about 70 tropical countries throughout tropical Asia, Africa, Latin America and Oceania. For most of these countries, albeit being an introduced species, teak represents a good opportunity to produce quality timber and is a major asset for the forestry economy attracting large investments from the private sector. Planted teak forests according to various estimates cover between 4.35 to 6.89 million ha. They are known to exhibit a wide range of origin-related variation in growth and wood characteristics. Breeding programs continue to be developed in many countries aiming at improving timber quality of teak planted forests. Most of them, however, are established with seeds of uncertain origin and quality and more recently with clones being produced in countries such as Brazil, Costa Rica, Côte d'Ivoire, India, Indonesia, Malaysia, Tanzania or Thailand.

1.2.2 Genetic Variation in Teak Forests and Considerations for Tree Improvement

Provenance variation for economically and ecologically important traits has been investigated over the last 60 years and was found to be huge, but far from fully explored. Part of the genetic diversity that has been lost in natural forests may still be found in planted teak forests, many of which originate from the early introductions of the species around the world. It is therefore of fundamental importance to further investigate and characterise teak genetic variation in planted and natural populations for breeding and mass propagation. Selection and testing of planting material continues to be highly relevant as an

[1] In alphabetic order: Hugh Brown, Ghana; Reinhold Glauner, Switzerland; Doreen Goh, Malaysia; Lars Graudal, Denmark; Mauricio Jerez, Venezuela; Nyunt Khaing, Myanmar; Michael Kleine, Austria; Walter Kollert, Italy; Yazar Minn, Myanmar; Olivier Monteuuis, France; P. K. Thulasidas, India; Przemyslaw Jan Walotek, Brazil.

integral part of any major planting program. Strategic plans at international, national and program level on the development and use of genetic resources ('genetic business plans') are important, whether in public-private partnerships, forestry investment schemes, or to the benefits of smallholder growers. The primary objective of such a plan should be to facilitate access to good quality planting material of well documented and reliable origin.

1.2.3 Origin and Global Dissemination of Clonal Material

Teak clonal forestry has demonstrated its efficiency for establishing fast-growing industrial stands of enhanced yields, good wood quality and high commercial value. The clonal option appears to be the best way to maximize returns on investments in the shortest possible time using outstanding and site-adapted genotypes. The main risk in this context is inadequate information regarding the genetic origin of the clones that have been mass propagated and planted. The ensuing threat is an erosion of the genetic diversity in planting material deployed for large-scale plantings, exposing them to greater risks of environmental impacts from climate change, pests and diseases.

1.2.4 Management of Natural Teak Forests

Natural teak forests cover an area of ca. 29 million hectares, nearly half of which grow in Myanmar. The natural teak forest area has declined substantially in all native teak growing countries mainly due to overexploitation (legal and illegal), agricultural expansion, shifting cultivation, population pressure, and grazing. In addition, the targeted removal of the best quality teak trees (creaming) from the natural populations has most likely resulted in the genetic impoverishment of residual stands. The failure of applied teak management systems is deemed a result of complex social, political, cultural, and environmental factors. As a consequence, the survival and sustainable use of the remaining natural teak forests is highly endangered.

1.2.5 Planted Teak Forests for High-Quality Timber Production

Planted teak forests need to be managed following a well-defined operational regime to achieve the desired production goals. Most important are good site selection, use of genetically improved planting material, adequate soil preparation, and the timely execution of silvicultural practices. Protection against forest fires as well as pest and disease management must be effective to avoid losses in productivity. Monitoring growth and yield dynamics is essential to facilitate adequate management responses. Sustainability (social, environmental, economical) including the provision of environmental services (e.g. watershed protection, biodiversity conservation, carbon sequestration) must be a key concern in the management of planted teak forests. The implementation of appropriate practices at every stage of development can help to achieve this goal.

1.2.6 Teak is Well-Suited for Smallholders

Teak-based small-scale production systems enable farmers to diversify farm production, support food security, generate income and reduce financial risk. Planted teak forests are an important alternative source of quality timber for wood industries. The potential of smallholder teak systems is hindered by limited access to good planting material, poor silvicultural management, difficult market access, and policy disincentives. These impediments must be addressed through improved market integration and policy support which will provide farmers with incentives to adopt better silvicultural and agroforestry management, e.g. intercropping with suitable crops.

1.2.7 Wood Production is Expected to Increase

About 2.0-2.5 million cubic meter teak roundwood is harvested annually from natural and planted forests although the annual wood increment of planted teak forests is estimated to be much higher. In the future, the production level is expected to increase, in particular from planted forests in Central and South America. In addition, India's large teak plantation estates will be expanded on unutilized marginal land to meet the country's growing domestic demand.

1.2.8 Wood Quality and Uses of Teak

The unrivalled qualities of teak wood make it one of the tropical hardwoods with high demand in luxury markets (e.g. for yacht building), applications in the construction industry (e.g. in India) and furniture manufacturing (e.g. in Indonesia, China). The internationally excellent reputation of teak was built originally upon durable high-quality timber from natural forests. Most planted teak forests however are being managed in shorter rotations. Plantation-grown teak does not yet have a high-quality image on the international market. In view of the declining supply of quality teak from natural forests, the long-term market prospects of plantation-grown teak appear promising provided that wood quality can be improved through the use of superior planting material, proper site selection and best management practices. The quality of plantation-grown teak roundwood is primarily determined by log dimension (diameter and clear bole length), and the proportion of heartwood in the cross-section. In terms of mechanical and physical properties (e.g. wood density, strength, shrinkage) some evidence suggests that wood harvested from planted teak is not inferior to naturally grown teak of the same age. However, the durability of teak clearly increases with age and the proportion of heart wood, irrespective of whether it is grown in natural or planted forests. Likewise, the aesthetic qualities of teak wood are largely determined by age, colour, grain, texture and the heartwood-sapwood ratio.

1.2.9 Trade and Certification

Between 2005 and 2014, the global annual trade of teak roundwood was more than 1 million cubic meters on average; the imports were valued at US$ 487 million per year, which is about 3 per cent of the value of the global timber trade (US$ 15.5 billion). The three major importing countries were India (74% of the total trade volume from more than 100 countries), followed by Thailand (16% of the total from about 15 countries) and China (10% per cent of the total from about 65 countries). Teak imports to Thailand have declined considerably lately, from a peak of 6.7 million cubic meters in 2004 to only 61,000 cubic meters in 2014. China and India, on the other hand, have increased their import volumes. Teak exports of Indonesia consist primarily of furniture. In 2010 the Indonesian teak furniture industry exported products valued at US$ 135 billion which constitutes over 1% of the global furniture trade.

One increasingly important consideration influencing trade in plantation-grown teak are forest management certification and legality issues. The timber markets of North America and Europe have responded legislatively through the Lacey Act (USA) and the European Union Timber Regulations (EUTR). Other markets will likely follow suit soon.

1.2.10 Lack of Uniform International Log Grading Rules Constitutes a Serious Market Constraint

The major challenge for teak growers is to produce internationally recognised quality wood. Despite considerable international debate over many years the global teak trade is hampered by a lack of international standards and consistency in measuring and establishing volumes and qualities for teak logs, which results in widespread uncertainty and confusion around teak investments.

1.2.11 Profitability of Teak Investments

Investments in teak plantations growing under suitable site conditions with genetically superior planting material and good management practices yield attractive and robust financial returns. Large-scale private teak plantation developers in Ghana achieve return rates of more than 10% (IRR). This is mainly due to substantial economies of scale and cost-reducing management interventions such as intercropping with food crops by nearby farming communities which reduces maintenance costs. Additionally, most investors raise their own seedlings, which apart from giving them control over the quality of planting material, also leads to lower unit costs.

1.2.12 Long-Term Price Trends

Teak price indices have been developed from publicly available long-term time series published in ITTO's Tropical Timber Market Reports since 1998. These indices measured in US$ per cubic meter indicate the superior status of natural teak timber as compared to plantation grown teak. In the Indian market the average cubic meter-related value of plantation grown teak is about half the value of natural teak from Myanmar. However, in recent years the market appears to have recognised a higher value for plantation grown teak, the price index of which has grown more rapidly than that of natural teak.

1.3 Recommendations

In view of the imminent threat of losing natural teak forests, it is imperative to organize and implement a global program for the conservation, improvement, development and sustainable use of teak resources. Such **Global Teak Support Program (GTSP)** would contribute to preserve the native teak resources still existing before they decline further. It would strengthen the understanding and knowledge of teak genetic resources, promote their sustainable use and management and contribute to develop and promote in-situ and ex-situ conservation programs through development assistance and research collaboration. Thus GTSP would contribute to the implementation of the Global Plan of Action on Forest Genetic Resources (GPA-FGR) and assist in achieving Goal 15 of the 2030 Agenda for Sustainable Development: *Sustainably manage forests, combat desertification, halt and reverse land degradation, halt biodiversity loss*; it would also support all Strategic Goals of the Aichi Biodiversity Targets of the Convention on Biological Diversity (CBD).

GTSP will have distinct tasks and program outputs, which are listed below in the form of recommendations for all relevant national and international forestry institutions and other concerned stakeholders:

1.3.1 Improve Statistical Database on Teak Forests

The available information and estimates on the development of natural and planted teak forests and the removals of teak roundwood are mainly based on FAO's Teak Resources and Market Assessment 2010[2]. This database

[2] http://www.fao.org/docrep/015/an537e/an537e00.pdf

must be improved to provide more reliable information on the development of teak resources and wood removals. Teak growing countries may consider integrating teak together with other commercial tree genera into the national reporting mechanisms and/or forestry statistics including national forest inventories, in order to monitor on a regular basis the development of teak forest resources. International forestry organisations may consider organising a remake of the 2010 survey on teak resources and markets.

1.3.2 Strengthen International Collaboration and Regional Networks on Forest Genetic Resources

International collaboration and regional networks on forest genetic resources (e.g. TEAKNET, APFORGEN, SAFORGEN, LAFORGEN) should be strengthened to develop action plans for the conservation and management of teak genetic resources. Such action plans might include:

- development of geographic, operational, and reliable genetic resource databases for characterizing every teak origin and seed production stand with location maps and common descriptors;
- development of appropriate quality standards and accreditation schemes for teak planting material involving the germplasm production and delivery sector, and current schemes for control of reproductive material (e.g. the OECD scheme on forest reproductive material);
- development of user-friendly decision support tools to guide the choice of planting material for specific sites (recommendation domains), in conjunction with market information services;
- measures to ensure that these standards and tools are mainstreamed with policy makers, extension services and the private sector, including manuals, policy briefs and other capacity building and extension material;
- development of indicators that are suitable to monitor the performance of delivery pathways with regard to standards including the performance and viability of plantings;

1.3.3 Monitor Genetic Improvement Programs and International Trade in Clones

Teak clone producers should be encouraged to select, identify and classify their material with a view to better monitor international trade and promote the production of a sufficient number of good quality clones of diverse genetic backgrounds that need to be reliably documented. In addition, the characteristics of clones that are traded on a global level should be subject to registration with an international authority. Tissue culture laboratories that have the capacity to produce good quality teak clones are to date only available in Asia and Latin America. It is expected that such facilities and know-how can be developed soon in other countries, in particular in Africa.

1.3.4 Improve the Management of Natural Teak Forests Towards Sustainability

- Strengthen forest governance and law enforcement by increasing transparency, by cooperating with local communities including other relevant stakeholders, and by mobilising funds for integrated land use planning, forest conservation, rehabilitation and restoration.
- Review and improve the existing silvicultural systems and practises, such as applying a flexible schedule of silvicultural operations in individual stand management; in addition, secure in-situ conservation stands of natural teak forests on a wide range of site conditions (e.g. climate, soil, elevation) and complement these conservation measures through the establishment of seed orchards and gene banks.
- Establish and implement performance and results-based compensation schemes (e.g. PES, REDD+) that are specifically designed to conserve and sustainably manage natural teak forests.
- Include social aspects into forest management, addressing tenure and user rights of forest communities, cost-and-benefit sharing arrangements as well as the empowerment of women, indigenous groups and minorities.

1.3.5 Support High-Quality Timber Production in Planted Forests

- Review and adapt government regulations and codes-of-practise to facilitate site and stand- adapted silvicultural management.
- Support the publication of teak growers' manuals in the respective local language, designed particularly for different target groups.
- Promote capacity building and awareness campaigns for various kinds of teak growers including smallholders and for operators.

1.3.6 Support Small-Scale Teak Production Systems for Smallholder Farmers

- National governments should encourage and support smallholders to plant teak through incentive programs, marketing support, formation of cooperatives, access to land titles or long-lease land tenure,
- Facilitate access to affordable sources of quality planting material for farmers,
- Support the formation of farmer-industry partnerships, support group marketing schemes, simplify timber trade regulations and eliminate extra-legal fees to enhance market access while reducing transaction costs,
- Regularly publish market information on teak prices and quality.
- Provide silvicultural and agroforestry management training through extension services for enhancing smallholders' technical knowledge and capacity.

1.3. 7 Further Investigate the Impact Of Silvicultural Management on Teak Wood Quality

The impacts of planting material and site selection as well as management practices on the quality of plantation and farmer-grown teak and its mechanical, physical and aesthetic properties should be further investigated through targeted professional research in different country contexts.

1.3.8 Improve the International Marketability of Teak

An international forestry or timber trade organisation should take the mandate to develop and adopt an agreed set of log grading rules in collaboration with global buyers to reduce market constraints and to improve the marketability of teak wood products taking into consideration the quality and dimensions of logs from plantations as well as from natural forests. By the same token, public and private teak producers and processors are encouraged to pursue voluntary certification schemes (management and chain-of-custody certification) if they wish to meet environmental, social and economic standards of responsible forest management and gain better access to North American and European markets.

1.3.9 Provide Impartial And Unbiased Cost-Benefit Analyses for Potential Investors

To be profitable, teak plantations require stable and predictable market conditions as well as good forest management practices with the objective to increase yields and reduce costs through suitable operational measures. In order to support the application of such a management regime impartial and unbiased cost-benefit analyses on teak investments should be made available through publications, internet portals or information leaflets. TEAKNET could take a leading role in publishing such information on-line on its website.

1.3.10 Improve Statistical Information on Teak Roundwood Production and Trade

A formalized exchange of information on the production and trade of teak would be of mutual advantage to importing and exporting countries. In this context reliable information on the dimensions, quality, origin and price of teak roundwood and major wood products in internationally acknowledged measuring units should be made available on a regular basis.

CHAPTER 2
Introduction

Walter Kollert[3] and Michael Kleine[4]

Since the 2nd World Teak Conference held in Bangkok in May 2013 the international partners IUFRO, FAO, and TEAKNET have been promoting the initiation of a large-scale international research, development and cooperation program to strengthen the conservation and sustainable use of teak genetic resources for the benefit of teak growers, forest industries, investors and local communities. In the same year, the 38th Session of the FAO Conference adopted the Global Plan of Action for the Conservation, Development and Sustainable Use of all Forest Genetic Resources. It identified the use of new technologies within the framework of bio-economy as a strategic priority to be supported by the international community. The envisaged Global Teak Support Program will build upon this initiative and contribute to the implementation of the Global Plan of Action.

The report "State of the World's Forest Genetic Resources" published by FAO in 2014 lists tree species that are considered national priorities by the reporting countries for the conservation and management of forest genetic resources. Teak (*Tectona grandis* Linn.F.) takes the top rank in this list in more than 20 countries. Economic value (including value of timber, pulp, food, wood energy, and non-wood forest products) is one of the main reasons for nominating the species as a priority for conservation and management. Though currently teak takes only a minor position in the total volume of world timber production and trade, it competes in the high-value hardwood markets and is a major strategic element in the forestry economies of many tropical countries.

Natural teak forests are estimated to cover ca. 29 million ha in India, Lao PDR, Myanmar and Thailand, of which almost half are located in Myanmar. The available old-growth, high-quality teak resources are under threat due to over-exploitation and conversion to other land-uses. The supply of quality teak logs originating from old-growth natural teak forests in Myanmar to overseas markets is in decline due to the impact of the log export ban in force since 1st April 2014, the decline of harvestable area in natural teak forests and the deterioration of the quality of naturally-grown teak. This has led to increased interest in establishing and sustainably managing planted teak forests.

Planted teak forests have attracted large investments from the private sector in Africa, Asia and Latin America. Globally, planted teak is the only valuable hardwood that constitutes an emerging forest resource. Planted teak forests according to various estimates cover between 4.35 to 6.89 million ha, of which more than 80% grow in Asia, ca. 10% in Africa, and ca. 6% in tropical America. Teak is known to exhibit a wide geographic variation in wood characteristics. Hence, in order to produce good quality teak in planted forests breeding programs have been established, mainly in Latin America and Asia, focusing on the selection of the desired wood-quality traits, including growth performance, clear straight bole, colour, grain, texture, stability, strength and durability. However, it is noteworthy that most planted teak forests are currently established using germplasm that is based on a very limited number of clones mainly originating in Costa Rica, Malaysia or Thailand.

The situation given with natural and planted teak forests calls for the implementation of a program for the conservation, development and sustainable use of teak genetic resources on a global level in order to preserve the still existing native teak resources before they decline further and to strengthen the understanding and knowledge of teak genetic resources, promote their sustainable use and management and contribute to the development

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and strengthening of in-situ and ex-situ conservation programs through research collaboration at national, regional and global levels. In the long-term, the programme is to help broaden the genetic base of available teak planting stock and thus to contribute to the establishment of resilient, high quality teak plantations. Overall, the implementation of the Global Teak Support Program (GTSP) will contribute towards achieving the Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development as well as the Aichi Biodiversity Targets of the Convention on Biological Diversity.

The global teak study presented in this report provides an analysis and evaluation of the current situation of the conservation and management of teak in both its natural range and in teak plantations.

The report was prepared and compiled by a team of IUFRO scientists and other teak experts from 11 countries. The major findings of the report are condensed in Chapter 1 “The Future of Teak - What Policy Makers and Managers Need To Consider”.

CHAPTER 3
Genetic Resources Conservation and Management

3.1 The Genetic Variation in Natural and Planted Teak Forests: Characterisation, Use and Conservation for the Future

Lars Graudal[5] and Søren Moestrup[6]

Executive Summary

The genetic variation in teak is large; exploration and testing of this variation have provided for significant gains in tree improvement. The observed quantitative differences between provenances of different origin reported from provenance field trials at several sites over the last 60 years are in line with more recent findings of genetic variation within and among teak regions at the molecular level. Provenance variation in economically and ecologically important traits is huge and far from fully explored. Natural teak forests have, however, declined and deteriorated. It is therefore important to develop gene conservation programmes that cover all parts of the gene pool as well as to further explore, mobilise and characterize the genetic variation in planted and natural populations for breeding and use in planting efforts. Selection and testing of applied planting material continues to be highly relevant as an integral part of any major planting programmes. A "genetic business plan" is important whether in co-operative organisations, private investment schemes, or in support of small-holder growers. To be successful, the sharing of impartial knowledge and access to reproductive material is crucial.

3.1.1. Introduction

Teak *(Tectona grandis)* is one of the globally most important tropical timber species both in natural forests and in plantations. It grows in different geographical regions under different environmental conditions, and variation can be observed in characters like leaf morphology, drought resistance, stem form and branch characteristics, growth increment, soil preference, the proportion of heartwood, wood structure, fibre length, strength, specific gravity, durability, wood extractives, wood colour, contents of minerals, and resistance to pests and diseases. The variation is a combination of genetic differences (among populations and among individuals within populations) and differences in the growing environments (soils, climate, and silvicultural practices). The major objective of the studies of genetic variation in teak was therefore to separate these effects and identify trees with attractive genetic features for propagation and use in plantation programmes, cf. *e.g.* Kjær, 2005.

The purpose of this chapter is to give a brief account of present knowledge of the genetic variation of teak from natural and planted forests. This knowledge is required both to inform decisions of which sources of teak to plant where and to identify the needs for conservation of the genetic variation for the future.

3.1.2 The Distribution of Teak

The first indicator of possible genetic variation is the pattern of eco-geographic variation. Teak has a large, environmentally diverse, and geographically separated, natural distribution range covering parts of India,

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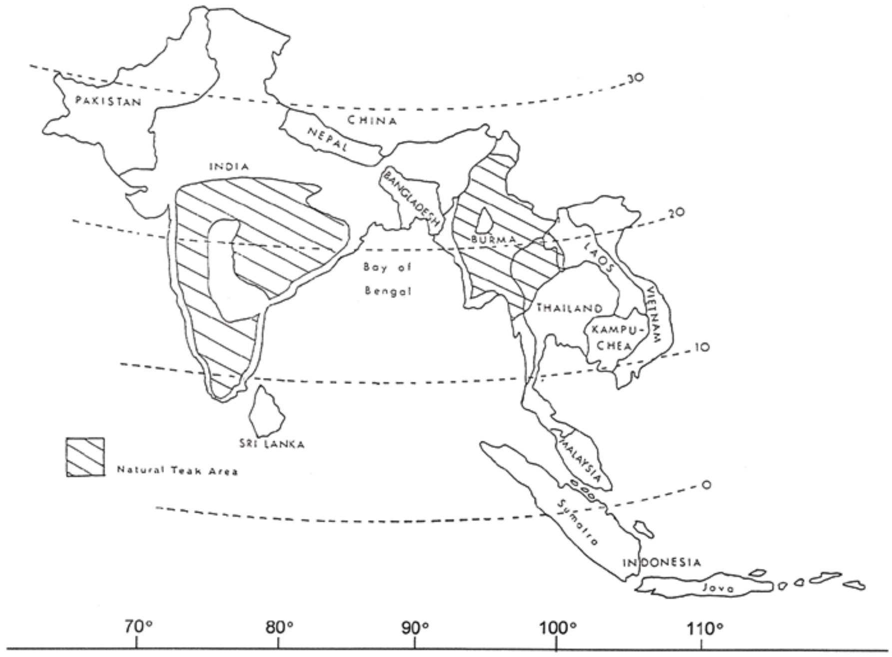
The natural distribution of teak (*Tectona grandis*) (Kaosa-ard, 1981, slightly modified according to Champion & Seth, 1968, and Keiding *et al.*, 1986). Figure 1



Myanmar, Thailand and Laos (Kaosa-ard, 1981); see Figure 1.

It also grows widely on Java, where it is considered introduced but naturalised over several centuries (Verhaegen *et al*., 2010).

The species is easy to propagate although low germination percentage often leads to very large seed demand (Kaosa-ard *et al*., 1998). The species possesses pioneer characteristics including fast juvenile growth, which makes it easy to plant and it grows well where climate and soil are appropriate. It grows predominantly in areas with an annual rainfall of between 1300 and 3800 mm (*e.g.* Pandey & Brown, 2000) on good fertile soils (*e.g.* Kaosa-ard, 1981 and Goh *et al.,* 2013). The natural habitat of teak usually shows a pronounced dry season of at least 5 months, but the species also grows in areas without pronounced dry season (*e.g.* Monteuuis *et al.*, 2011). Good wood properties can be obtained in plantation grown teak even though wood properties to some extent depend on age (Bhat, 2000; Bailléres & Durand, 2000).

The high value of the timber and the easy plantation establishment have made it one of the most important tree species for planting in the tropics, also outside its natural distribution area (Keogh, 1996). Reportedly, teak grows in more than 60 countries (Kollert & Cherubini 2012; Midgley *et al.*, 2015); see Table 1, planted teak forests by region.

Thus, global exchange of reproductive material of teak has provided an important option for forestry and wood-based production worldwide (Kjær & Graudal, 2010; Koskela *et al.*, 2010 and 2014). Plantations are expected to be the primary future source of teak wood (Kollert & Walotek, 2015).

3.1.3 Formation of landraces

The high potential of teak for plantations was early recognised in many countries, and seed therefore transferred mainly from India and Myanmar to Africa and Central America more than one hundred years ago (Koskela *et al.* 2014). It was introduced before 1900 to Nigeria (Egenti, 1978), West Indies, Trinidad (Keogh, 1979) and Papua New Guinea (Cameron, 1968); just after 1900 to Tanzania (Wood, 1967), Togo (Chollet, 1958) and Ghana (Chollet 1958, Lane 1956 in Odoom 2002); and during the following decades to Côte d'Ivoire (Tariel, 1966), the Sudan (Hall & Williams, 1956) and a number of additional Central and South American countries (Keogh, 1979, 1980, 1981).

Most of the early introductions were small and served two important purposes: (i) to verify the suitability of the species at different sites, and (ii) as seed sources for future propagation and large-scale deployment (Kjær & Graudal, 2010; Koskela *et al.*, 2010 and 2014). The introduced seed originated from multiple sources and this contributed to the development of landraces in Africa and Central America.

The origins of these landraces are not well documented, but historical records (cf. above) and genetic studies have shed some light on the possible routes of introduction, and the likely sources of germplasm (Koskela *et al.*, 2014).

The African landraces are reported to originate from multiple and diverse seed sources in India, Myanmar and possibly Java (Wood, 1967). Verhaegen *et al.* (2010) indicate that North India may have been an important source for many African introductions. Other studies on genetic diversity (*e.g.*, Kertadikara & Prat,

Table 1

Estimated areas of teak plantations, after Midgley et al., 2015, based on FAO, 2010 and ITTO, 2009. The FAO study (Kollert and Cherubini, 2012) is based on responses from 48 of 60 teak growing countries. The ITTO report was also incomplete. The 'moderated estimate' by Midgley aims to be closer to the global reality than the deliberately more conservative estimates of FAO and ITTO.

Area (1,000 ha)			
Region/country	**FAO (2010)**	**ITTO (2009)**	**Moderated estimate**
Asia			
India	1,667	2,561	2,561
Indonesia	1,269	1,470	1,470
Burma	390	0	390
Thailand	128	836	836
Laos	-	0	15
Bangladesh	73	-	73
Others	-	726	726
Asia total	3,527	5,593	6,071
Africa			
Ghana	214	40	214
Nigeria	146	74	146
Côte d'Ivoire	52	66	66
Benin	26	0	26
Sudan	-	25	25
Tanzania	-	-	10
Others	-	51	51
Africa total	470	256	538
Latin America			
Brazil	65	50	65
Panama	55	0	55
Ecuador	45	0	45
Costa Rica	32	30	32
Guatemala	28	0	28
El Salvador	-	-	-
Others	-	53	53
Latin America total	225	133	278
Global total			
	4,346	5,982	6,887

1995, Shrestha *et al.*, 2005 and Sreekanth *et al.*, 2012) have provided further information on genetics of African landraces, but have not revealed their exact origins.

In Central America, the first introduction was to Trinidad in 1913, where the seed probably came from Myanmar and India (Keogh, 1980). In the 1920s, teak was planted in Panama using a small seed lot supposed to be from India (Keogh, 1980, cf. Koskela *et al.* 2014). Seeds were then collected from these plantations for further introductions in Central America (Koskela *et al.* 2014).

Indonesian teak appears from a genetic study by Verhaegen *et al.* (2010) to be linked to the eastern-most part of the natural distribution areas in Central Laos, in contrast to historical records that suggest teak was imported from South India. Newer studies, however, place the origin of Indonesian teak further west in North Western Thailand (Hansen *et al.*, submitted).

In the Pacific particular interest is associated with the origin of some of the teak grown on the Solomon Islands because of good general performance of clones presumed, although not confirmed, to originate from Tennaserim in southern Myanmar via Papua New Guinea (Goh *et al.* 2005, 2007, Goh & Monteuuis, 2009).

Land race formation has to a large extent been a random process. It has been fairly arbitrary from where the first introductions came, and resulting local gene pools are often based on multiple introductions. Different stands in a country may have completely different origins. In some cases the local landraces are relatively low performers (*e.g.* Kjær & Lauridsen, 1996), in others they perform quite well (*e.g.* Pedersen *et al.,* 2007). Reasons for low performance may be dysgenic selection (*e.g.* from early and abundantly flowering but otherwise low quality trees) and inbreeding (due to small population sizes acting as bottlenecks, reducing the genetic diversity); and for better performance as a result of outbreeding vigour (Kjær & Siegismund, 1996), rapid adaptation to the local growth conditions, or simply because of a good initial provenance.

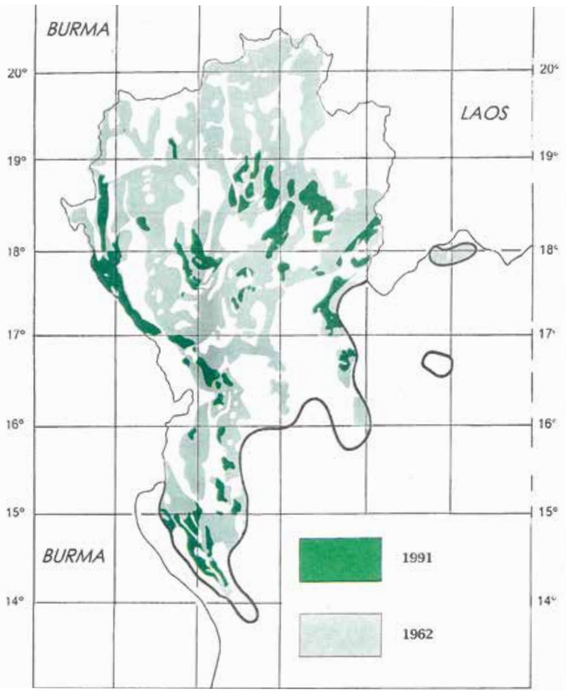
A recent study of 17 landraces from Latin America, Africa and Indonesia by Hansen *et al*. (submitted) show that none of the studied land races seemed to have origin in South and West India or in Northern Myanmar and there was no indication – except in one case – that substantial genetic bottlenecks had occurred during the translocation of teak. In contrast, variation in diversity levels among teak landraces probably mainly reflects their areas of genetic origin. The seven studied landraces from tropical America were genetically quite similar – and thereby in accordance with the proposed limited number of introductions.

3.1.4 The State of the Genetic Resources of Teak

Whereas the teak resource in countries outside the original distribution area has been increasing, the natural forests of teak have declined and a lot of the original forests have been completely lost, with many of the remaining patches logged over (Kollert & Cherubini, 2012). In Thailand, for instance, more than two thirds of the forest area disappeared between 1960 and 1990 (Graudal *et al.*, 1999), see Figure 2. However, this trend was reversed with the Thai logging ban in 1989 (Kollert & Cherubini, 2012).

Figure 2

Past and present distribution of mixed deciduous forest with teak (*Tectona grandis*) in Northern Thailand



Source: Graudal et al., 1999

The extent of natural forest is shown in Table 2 (Kollert & Cherubini, 2012).

Except for Thailand (Graudal *et al.,* 1999 and Steber, 1998 (in Kollert & Cherubini, 2012)), no assessments of the original distribution of the natural teak forests seem to be available in published form. The attempt to map past and present distribution in Northern Thailand in Figure 2 was based on historical distribution maps (RFD 1962, 1983, 1993, 1994 and 1995). Similar maps are likely to be available for other areas, so it may be possible to get an idea about the original distribution, which then fairly easily could be compared with current distribution based on remote sensing.

It is a major concern that severe loss of natural teak forests and the potential negative effects of previous selective logging of straight trees in the remaining forests could have led to genetic erosion of the genetic resource (Graudal *et al*., 1999). On the other hand, wide-scale plantations and domestication programmes have probably captured important diversity. Hundreds of large and very straight trees were *e.g.* identified and propagated in Thailand during the 1970s and 1980s (Kaosa-ard *et al.*, 1998) and silvicultural thinning in favour of straight and vigorous growing trees in teak plantations may to some extent have reversed genetic effects of previous negative selection for stem form if straight trees were logged selectively while native forests were overexploited. Therefore, existing teak plantations and breeding programmes may

Table 2

Area of natural teak forests (1,000 ha) by country according to Kollert and Cherubini, 2012.

Country	>1960	1976/1979	2010
	1,000 ha		
India	?	8,900	6,810
Lao PDR	?	70	1.5
Myanmar	?	14,600	13,479
Thailand	16,000	5,850	8,744
Total	**?**	**29,420**	**29,035**

be an important gene pool for *ex situ* conservation of important genetic resources.

Effective gene conservation programmes will support the availability and the deployment of the most appropriate genetic resources to match production site conditions (soil and climate) and systems (small scale, large scale, monoculture, intercropping) and contribute to providing for the best wood products under both current and future climatic conditions. The latter is important to be taken into account when it comes to considering for which areas the species may be most appropriate in the future (*e.g.* Booth & Jovanovic, 2014; Alfaro *et al.*, 2014).

As a consequence there has been a great interest in characterising the genetic resources of teak, identifying which sources of teak are best to use for planting on a site, in order to conserve the most important genetic resources and develop more productive and more resilient planting material for current and future planting programmes.

3.1.5 Characterising the Genetic Resources of Teak

The interest in characterising the genetic resources of teak goes back several decades, but systematic research and development activities started only long after the species was introduced from Asia to other regions of the world more than hundred years ago.

The genetic variation has been assessed by analysis of morphological and metric characters in field trials and laboratory analysis of variation in biochemical and molecular markers (Graudal *et al.,* 1999). For conservation and monitoring purposes, analysis of eco-geographic variation has been applied as supplement to the often scattered genetic information available based on the assumption that differences in ecological conditions are likely to be reflected in variation in traits of importance for fitness (Graudal *et al.,* 1997 and 2014).

3.1.5.1 Quantitative Genetic Variation Observed in Field Trials

Tree improvement was initiated in India, Thailand and Indonesia in the 1950s and 1960s. Quite comprehensive exploration, collection and testing took place in these countries and improvement activities were subsequently initiated in many other countries, e.g. China, Malaysia, West Africa, Tanzania, Australia, Central and South America (Goh *et al.* 2007, Hansen *et al.*, 2015, Kjær *et al.* 2000, Murillo & Badilla, 2004), cf. also section 3.1.3 and Table 1.

There is no single series of provenance trials that provide exhaustive information on the variation among geographic origins. Likewise, no comprehensive overview of the findings from the many provenance trials is available. Keiding *et al.* (1986) and Kjær *et al.* (1995) compiled and analysed results from a coordinated, international series of provenance trials initiated in the late 1960s, but none of the single trials included origins from all parts of the distribution area and the individual trials represented different environmental conditions across three continents.

An attempt to summarise some trends and patterns is presented in Table 3. The observations comprise a mix of natural sources and landraces across a diverse set of environments.

There are several other quantitative genetic studies than those referred to in Table 3.

Studies from progeny- and clone field testing have shown modest heritability for volume, height and diameter growth at ages 3-6 years (Callister & Collins 2008, Callister 2013, Murillo & Badilla 2004). However, heritability increased up to an age of about 9 years in two field trials with open pollinated families and sufficient variation in height, diameter and volume (Chaix *et al.* 2011, Monteuuis *et al.*, 2011), indicating a potential for improving growth through selection depending on the genetic correlation up to the age of harvest.

Studies on genotype-environment interactions concerning growth from clone- and progeny field tests are sparse and with a small number of genetic entities, but indicate some degree of genotype by environment interaction (Goh *et al.*, 2013, Hidayati *et al.*, 2013). Nevertheless, Goh & Monteuuis (2012) points also to the opportunity of finding genotypes that perform well in a wide range of environments based on the practical experience with eight clones (cf. also Table 3).

Opportunities to improve stem straightness at the juvenile stage are possibly small (Callister & Collins 2008), but may improve with age (Danarto *et al.*, 2000) and progeny from clonal seed orchards with selected trees tended also to have better external stem quality in the studies of Chaix *et al.* (2011) and Monteuuis *et al.*, (2011). The genetic correlation between stem straightness and growth is moderate (Danarto *et al.*, 2000; Callister & Collins, 2008, Monteuuis *et al.* 2011, Chaix *et al.*, 2011, while selection for late flowering is efficient to improve (increase) forking height (Callister 2013).

Studies of Mandal & Chawhan (2005) and Narayanan *et al.*, (2009) show a high degree of genetic variation in heartwood percentage and suggest a high potential of using phenotypic selections to obtain substantial genetic gains in heartwood percentage.

Lessons learned from the field trials over the past approximately 60 years are thus that variation between provenances can be significant concerning adaptation, growth, external stem quality and wood quality. The choice of provenance for a given site can therefore have an important impact on the success of the plantation programme, but the present level of knowledge will rarely be sufficient to recommend a specific choice of seed source for a given site outside the natural distribution area of teak. The field trial series show the difficulties of predicting how a provenance will perform based on match between seed source and plant site climate.

The published studies indicate an important potential for gain through selection *e.g.* for better growth, stem form, heartwood percentage, and delayed flowering to reduce forking. Selection for growth seems to be positively correlated with stem straightness. Special interest

Table 3

An attempt to identify some general findings from various field studies, including selected provenance and progeny trials and one set of clones, adapted from Kjær 2005 and Kjær *et al.* 2011, modified and updated with new information.

Series/trials/studies	General findings
The All-India provenance trials initiated in 1930, including 11 provenances in trials at 13 locations spread in India (Mathauda 1954). Later a new series was established in 1980-81.	Early results indicated that local provenances will likely perform best, but that introductions from moist India may grow better. South West India (Nilambur) tended to prove more stable and vigorous and always with some few superior trees surviving on more extreme sites.
Indonesian series of provenance trials established in Indonesia in the 1930s, and later in 1959 (Suhaendi 1998).	In general possible to identify Indonesian landraces with as much growth as the best exotics. Indonesian landraces of moderate external stem quality. Two Lao provenances proved superior concerning stem form and branching. An Indian Malabar provenance showed generally good growth, but was characterized by many branches.
Chinese series of provenance field trials initiated in 1973. Provenances tested included old introductions to China from Burma, Malaysia, Indonesia, and India, together with new introductions from Burma, Thailand and India. (Bingchao *et al.*, 1986)	A South-West Indian provenance (Sungam, Kerala) produced 50% more volume than the best Burmese provenance and showed better drought resistance compared to Burmese and Thailand provenances in nursery field trials.
Provenance field trials at Huey Tak in Thailand with a large number of local provenances established in 1966/69 assessed at age 15 (unpublished data, here based on results presented in Graudal *et al.*, 1999, Annex 1).	Multivariate analysis of the trial at Huey Tak confirmed significant differences between origins within the natural distribution area of teak in Thailand. The variation did not match floristic regions, but revealed a tendency to East-West clonal variation. The pattern seems in accordance with results from the genetic marker study by Hansen *et al.* 2015.
International Danida Forest Seed Centre (DFSC) coordinated a series of field trials including a large number of provenances tested on several sites, mainly outside its natural distribution range. A coordinated assessment of 18 trials was made at age 9 and repeated on 7 sites at age 17. (Keiding *et al.* 1986, Kjær *et al.* 1995, Kjær & Lauridsen 1996)	Indonesian provenances in general had good survival and growth, while provenances from Kerala (South West India) overall combined good growth, high stem quality, fine branches, but with important exceptions. Thai and Laos provenances did fine in Thailand, but were among the slower growing outside Thailand, although in general with good stem form and fine branches.
Two 28-year-old field trials in Ghana (semi-moist and dry). Both trials were part of the DFSC coordinated field trial series (Hansen *et al.*, 2007).	Nilambur (South West India) superior on both sites concerning stem straightness and low buttressing. Highly superior growth on the semi-moist site and moderate growth on the dry site. Indonesian landraces perform differently at different sites. Bangsri Pati highly superior growth on the semi-moist site and moderate on the dry site.
One 28-year-old and one 32-year-old field trial in Cotê d'Ivoire (semi-moist sites), but different material on the two sites. The 28-year-old field trial was part of the DFSC coordinated field trial series (Hansen *et al.*, 2007).	Nilambur superior (South West India) concerning growth, stem straightness, buttressing and epicormics Masale Valley (South West Indian) superior growth, reasonable buttressing, but otherwise poor external stem quality. Tanzanian landrace Kihuhwi superior concerning growth, but average in external stems quality.
One field trial in Tanzania, semi-moist conditions (Pedersen *et al.*, 2007).	South West Indian provenance ('Topslip') superior concerning growth and stem straightness.
Two field trials in Malaysia, very moist, no particular dry season (Chaix *et al.*, 2011; Monteuuis *et al.*, 2011; Goh *et al.*, 2013).	The Solomon Island landraces Arara and in particular Viru were superior as regards growth, fork height and stem straightness compared to a number of Indian Karnataka provenances and families from open-pollinated trees in India, Tanzania, Thailand and Cotê d'Ivoire. But large variation between families and with a number of families superior to the Solomon Island landraces as regards external stem quality and growth. Open pollinated progeny from trees in clonal seed orchards from drier parts of India and Thailand were in general slow growing on the test site.

Series/trials/studies	General findings
Solomon Islands, five provenances from the Island, two from India, one from Thailand, one from Nigeria, and one from Honduras (Pedersen 2010).	At moist conditions, age 7 years. Landraces of Solomon Island superior concerning growth compared to provenances/landraces from India (Nilambur), Thailand, Nigeria and Honduras.
Ten provenances from Myanmar tested on four sites in Myanmar seven years after planting (Lwin *et al.*, 2010)	Provenances from the southern region of Myanmar generally perform better than those from the north. Results in accordance with East-West and North-South differences also observed in earlier Thai provenance trials (Graudal *et al.* ,1999). The clustering also seems in accordance with the genetic marker study by Minn *et al.*, 2014.
Eight clones selected in the Solomon Island landrace on Sabah (Goh *et al.*, 2010)	Selected for growth, external stem quality and high percentage of heartwood. Have proved good growth and quality in widely different environments (Goh & Monteuuis, 2012).

is associated with improvement of heartwood quality and percentage that would allow harvest of smaller logs.

Very little is known about genotype by environment interactions which speak in favour of testing selected genotypes at the local level before large-scale deployment in areas where teak is grown as an exotic species.

3.1.5.2 Genetic Variation Revealed by DNA Markers

There have been several studies based on genetic markers, but most studies have only covered a limited part of the distribution area or been based on small sample sizes (see e.g. Hansen *et al*. 2015). However, recently several studies have provided a more comprehensive overview of variation within and among the major teak regions (Sreekanth *et al.,* 2014; Minn *et al.,* 2014; Hansen *et al.,* 2015; Vaishnaw *et al.,* 2015, Thwe-Thwe-Win *et al.,* 2015a, 2015b; Nair *et al.,* 2015; Minn *et al.,* 2016; Thwe-Thwe-Win *et al.,* 2016, Huang *et al.,* 2016; Behera *et al,*. 2016).

One of these studies (Hansen *et al*., 2015) cover populations from all major parts of the whole natural distribution area. The findings are summarised in Figure 3. Based on the analysis, Hansen *et al.* (2015) confirm previously reported differences among populations in diversity, and identify a West-East pattern where the provenances from the semi-moist East coast of India have the highest genetic diversity and the Laotian provenances have the lowest (Fig. 3). The study further suggests that the natural distribution area can be roughly separated into six major genetic clusters (Fig. 3). The DNA based clusters in general make sense when compared to the findings from the various provenance trials (Table 3). Still, huge environmental variation exists within the major clusters, where the different populations within each cluster can have become adapted to quite different growth conditions and seed source testing and gene conservation must therefore be based on a much finer scale.

3.1.6 Discussion and Conclusions

The genetic variation is an important resource for breeding, but also for the ability of species to adapt to future climatic conditions, and the observed high levels of variation within and among genetic origins of teak highlight the importance of a wise use and conservation of the genetic resources of the species. It is important to develop gene conservation programmes that cover all parts of the gene pool, and these pools can be further explored and mobilised for practical breeding programmes.

This mobilization of the gene pool can take place both in the remaining natural forests, but a significant *ex situ* resource also exists in plantations and breeding programs outside the natural distribution range of teak. Given the randomness in landrace formation of the *ex situ* resource combined with the risk of being narrowly genetically based, uncritical use in plantation programmes of local landraces of unknown origin is not advisable.

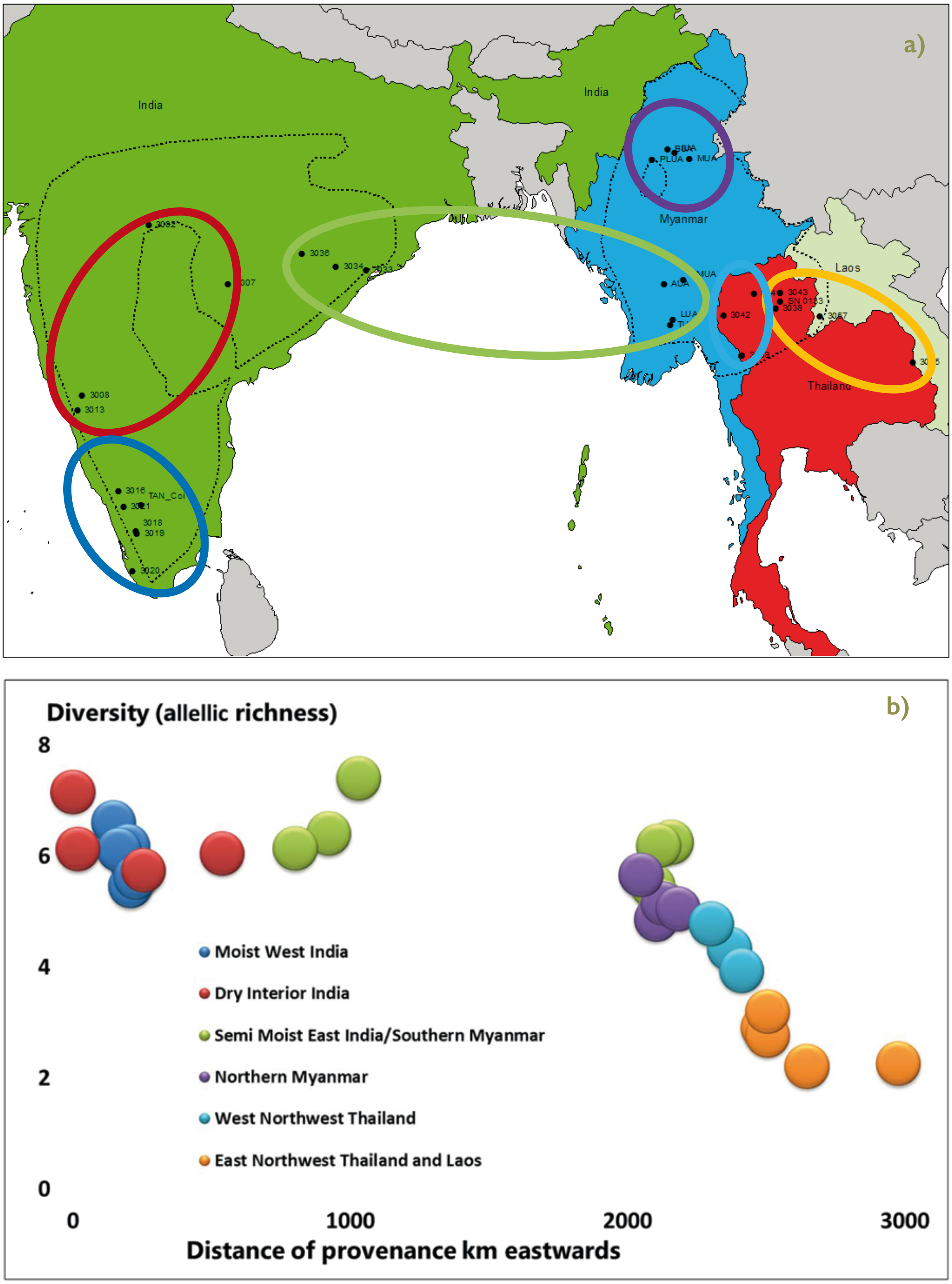
Field testing will remain important, and if coordinated between sites, regions and countries, it will be possible to estimate level and patterns of genotype by environment interaction: is it the same genotypes/seed sources that are superior at different site types? And if not, which site types or land use types can be combined into common breeding and deployment zones. It also speaks in favour of local or regional efforts in development of superior seed sources/ clone collections and coordinated testing programmes across sites in a given area (Kjær *et al*., 2011).

Local testing and systematic collection of growth data related to the applied planting material will still be relevant. Development of local "genetic business plans" will include consideration on what to plant in the absence of local results, but also a plan for simple data "harvest" mechanisms and how to adapt future management decisions according to the gathered experience.

Establishment of shared teak gene pools in teak-plantation environments based on co-ordinated, multi-locational trials of seed sources and clones may serve testing and *ex situ* conservation at the same time. Such an effort is currently being attempted for Central America

Graphic presentation of genetic analyses of 29 provenances of teak across a West-East gradient from India, Myanmar, Thailand and Laos.

Figure 3



a) The analyses found three main clusters of diversity, each with two sub-clusters: Interior and Western India (divided in Dry Interior (red circle), and Moist West (blue circle), Eastern India and Myanmar (divided in Northern Myanmar (purple circle), and Semi Moist East India & Southern Myanmar (green circle)), and Thailand and Laos (divided in West Northwest Thailand (light blue circle), and East Northwest Thailand & Laos (orange circle)).

b) Diversity was highest in Eastern India but without any clear pattern there. In the Eastern region there was a strong continuous variation ("cline") with decreasing diversity going east. Colour codes refer to clusters in part A of the figure.

Source: Hansen et al., 2015.

by CAMCORE (CAMCORE annual reports 2012-2014); following their cooperative model (Dvorak *et al.,* 1996).

Another option consists of more business-oriented alliances with long-term investors, where the idea of "genetic business plans" could be implemented as part of large-scale plantings to assure best-informed choice of quality planting material in teak under uncertainty of genotype performance (risk management, cf. Burdon & Aimers-Halliday, 2006).

Last but not least, the sharing of impartial knowledge and access to reproductive material is crucial. Objective information to growers and investors is required to avoid "teak.com bubbles" which occurred in India in the 1990s, when private sector enterprises were promised exaggerated high returns of investment in so-called high tech, high input short rotation ventures (Chundamannil, 2007). The availability of material and information to communities and farmers will be of specific importance in some areas, since they may have limited resources for their seed procurement activities. Obviously, organisations like FAO, IUFRO, Teaknet and the CGIAR may have roles to play. The continued research programme of CGIAR on Forest, Trees and Agroforestry (FTA) will in phase II, 2017-2022, implement a sub-programme on Tree Genetic Resources to bridge production gaps and promote resilience, which could be relevant in this context.

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3.2 Origin and Global Dissemination of Clonal Material in Planted Teak Forests

Olivier Monteuuis[7] and Doreen Goh[8]

Preamble

Anticipated for a long time, teak clonal forestry has finally become a reality. Teak clonal plantations have rapidly expanded over the past years, driven primarily by private commercial interests. This could explain why a lot of information is kept confidential. This report should therefore not be considered as exhaustive and definitive, but more as an eye opener on certain aspects of teak clonal plantations.

3.2.1 Background

3.2.1.1 Rationale of Cloning Teak

Propagation by seeds remains for teak as for any other species the easier, the more natural and efficient way to produce new genotypes. This is essential for guaranteeing a suitable genetic diversity and also for genetic improvement through wise breeding activities. Propagating teak through seeds has been practiced for centuries, with the possibility of storing the seedlings in the form of "stumps" when necessary, for instance while waiting for suitable planting conditions (Kaosa-ard, 1986). However, mass producing teak planting stock by seeds is hindered by serious handicaps such as:

i) A negative correlation between the onset of fruiting/seed production and clear bole length (Kaosa-ard *et al.* 1998, Callister 2013), affecting the commercial value of the latter. Practically, seeds collected from early flowering individuals will ultimately give rise to poor quality trees.
ii) A quantitatively limited seed production that is prone to tree, year and site variations (Wellendorf and Kaosa-ard 1988, White, 1991).
iii) An overall low and unpredictable seed germination capacity that rapidly declines with time after collection, although differences may exist between seed sources (Kaosa-ard, 1986, White, 1991).
iv) A substantial variability among individuals, even when derived from the same mother tree, affecting traits of major economic importance like growth, trunk form, technological and aesthetic characteristics of the wood (Bedel 1989, Chaix *et al.*, 2011, Monteuuis *et al.*, 2011).
v) Limited accurate knowledge about the inheritance of economically significant traits making the ultimate gain uncertain, notwithstanding the time constraints associated with sound breeding programs (Kjaer and Foster, 1996, Chaix *et al.*, 2011, Monteuuis *et al.*, 2011).

By contrast, cloning consists in duplicating genotypes, theoretically unlimitedly by asexual or vegetative propagation methods, while preserving through mitotic divisions their original genetic make-up. Consequently, all their characteristics, including those of great economic impact which can be poorly inherited by seed propagation, will be transferred to the offspring. The resulting crop will uniformly exhibit all the features of the original tree it arises from. This emphasises the importance of reliably selecting candidate plus trees to be cloned, the so called CPTs, which must be really outstanding for economically important traits, the more the better (Murillo and Badilla 2002, 2004, Goh and Monteuuis 2005, Goh *et al.*, 2007).

Moreover, vegetative propagation can be applied to any individual that does not produce fertile seeds, either because it has not entered the mature stage yet, or due to unfavourable environmental conditions.

Theoretically, for teak as for any other tree species, cloning can be useful for research as well as for commercial planting (Monteuuis and Goh 1999). More specifically, teak clonal plantations are expected to produce high yield of premium and uniform quality timber in the shortest delays. Practically, this will depend upon the capacity of the species to be efficiently mass clonally propagated.

3.2.1.2 From Theory to Practice: the Determining Impact of Efficient Mass Clonal Propagation Techniques

The mass production of teak clones, especially from mature selected trees has for a long time been hindered by the lack of efficient technology. Grafting has been practised for decades on a small scale mainly for establishing clonal seed orchards or "CSO" in various countries (White 1991, Monteuuis and Ugalde, 2013). A few experiments have demonstrated that teak genotypes of various ages could be propagated *in vitro* but not with the efficiency required for mass production (Gupta *et al.*, 1980, Mascarenhas and Muralidharan, 1993), except in Thailand, where young seedlings were used under the Forest Royal Department during the 1980s (Kaosa-ard *et al.*, 1987). However, the field behaviour of such tissue culture-derived plantlets was not sufficient to offset the production cost, and as such, seedlings have remained the

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main source of planting stock for national teak plantation programs in this country.
The situation changed dramatically during the 1990s with the development of efficient nursery and tissue culture techniques adapted to the mass production of clones by rooted cuttings and microcuttings of any selected teak tree, regardless of its age (Monteuuis 1995, Monteuuis *et al.*, 1995, 1998). Moreover, the possibility to export tissue-cultured teak microshoots to international destinations opened up wide market prospects mainly under the impulse of two big private companies: Thai Orchids from Thailand and YSG Biotech (www.ysgbiotech.com) – ICSB at that time – from Sabah, East Malaysia. Amazingly, although Thai Orchids activities on teak remained very limited in its native country, the company expanded quite rapidly, generating most of its business returns at the international level thanks to a very dynamic marketing policy and through partnerships with Monfori (subsidiary of Monsanto) in Indonesia, Forbio in Australia and Tropbio in Malaysia.

3.2.2 Selecting and Propagating the Clones

3.2.2.1 Selecting the Genotypes to be Vegetatively Propagated

The selection of CPTs for clonal commercial plantations will be based primarily on economically-important traits such as vigour, growth rate, bole shape, branchiness and wood quality, taking advantage of non-destructive assessment methods (Murillo and Badilla, 2002, Goh *et al.*, 2007, Kokutse *et al.*, 2016). As a general rule, the larger the difference with the rest of the population, or the stronger the intensity of selection, the greater the commercial gain. Several of these traits are expressed and thus can be assessed only from developed or mature enough trees, as too many uncertainties are associated with juvenile trees or seedlings to allow for a reliable selection. In addition, for safer clonal deployment especially with regard to disease risks, the CPTs must not be too genetically close.

Also to be considered are genotype x site interaction issues: to what extent can these traits be modified by planting site conditions? This will basically depend on the capacity of the genotype initially selected by phenotypic assessment in a specific site to adapt to other environments. To answer this question is the main purpose of properly set up clonal tests, notwithstanding the time, space, plant material and human resources required.

The genetic quality and the diversity of the base populations or more seldom the breeding populations from which the CPTs are selected are essential (Goh and Monteuuis, 2005, Goh *et al.*, 2007), although attractive features of a few isolated CPTs can give rise to success stories (Goh and Monteuuis, 2012). The quality of the CPTs has always been an overriding concern for YSG Biotech which started its clonal propagation program from mature CPTs which can be more reliably selected than juvenile seedlings or seeds. The initial gene pool limited to a few individuals from the Solomon Islands has rapidly and considerably been enriched by new teak genetic origins from various sources (Goh and Monteuuis 2009). The company currently owns the richest teak gene pool from which new clones have been selected to be field-tested or sold to any potential buyers who can have access to the well documented genetic origin of each clone.

3.2.2.2 Propagation Strategies: Bulk Versus Separated Clones

There are basically two options for vegetative propagation of genotypes. This can be done without maintaining any individual identification, as a mixture. This strategy, referred to as “bulk propagation”, differs essentially from clonal propagation whereby the genotypic identity is rigorously and individually preserved through all the successive cycles of the clonal propagation process, and which may last several centuries in certain cases.

In contrast to clonal propagation, the bulk option does not require any strict and clear labelling of each genotype or clone during the successive cycles of the propagation chain, then during the subsequent nursery and field steps. Its main advantage is to make all these operations easier, simpler and cheaper.

Vegetatively propagating a mixture of unidentified genotypes will maintain a certain degree of genetic variability, depending on the number of genotypes involved from the very beginning. Consequently, the resulting wood populations may look phenotypically heterogeneous, teak being prone to noticeable phenotypic differences between genotypes. However, successive generations of bulk propagation will very likely result in a significant reduction of the original genetic base, which may eventually consist of only one genotype. This is due to genotypic differences in the multiplication and rooting rates, the genotypes producing the more shoots the higher the capacity for adventitious rooting supplanting ultimately the others.

Clonal propagation involving rigorous genotypic identification prevents such risks of losing control of the genetic fidelity of the material under propagation, the numbers of clones and of their respective clonal representatives remaining known throughout the entire propagation process. This information is of great importance in the further use of the propagated plant material, be it for sales or field establishment, in the form of monoclonal blocks or of polyclonal varieties. These consist of a mix of selected clones, each being represented by an accurate number of plants. Polyclonal varieties differ in this respect from bulk propagation-issued populations of more uncertain genetic composition.

3.2.2.3 Techniques

Several vegetative propagation techniques have been successfully applied to teak. Although useful for mobilizing and clonally propagating in few numbers mature genotypes, layering and grafting are not applicable to large-scale clonal propagation of teak. Furthermore, the drawbacks resulting from the combination of two different genotypes for grafted clones should not be underestimated (Monteuuis and Ugalde, 2013).

Such hindrances can be overcome by the use of self-rooted teak clones mass produced by efficient rooted cuttings or *in vitro* micropropagation methods as described hereinafter.

Propagation by Rooted Cuttings

Rooting the first generation of shoots collected directly from *in situ* CPTs, also referred to as the mobilization phase, is considered the most critical step, especially when the CPTs are old enough to be reliably selected for economically important traits. The "stick method" developed in Sabah had helped to achieve this goal (Monteuuis *et al.*, 1995) and was preferred as more conservative than coppice shoots arising from the stump of the selected tree once this latter had been felled (Palanisamy and Subramanian, 2001, Singh *et al.*, 2006, Husen and Pal, 2007). The first few rooted cuttings obtained are used as intensively managed stock plants and this during 2 or 3 successive cycles of serial propagation by rooted cuttings until the material will be sufficiently physiologically rejuvenated to be used for clonal tests or large-scale plantations. Unlike many species, teak rooted cuttings develop true-to-type in absence of plagiotropic growth symptoms.

Developed first in Sabah (Monteuuis, 1995; Monteuuis *et al.*, 1995), this technique has been proven to be quite efficient and cost-effective in several countries for mass-clonally propagating any teak plus tree regardless of its age providing:

i) Suitable nursery facilities as described in Monteuuis (2000) are available, emphasizing the usefulness of a reliable mist system for rooting the cuttings and thereafter, facilitating their acclimatization.
ii) The cuttings and then the stock plants are judiciously and rigorously managed by competent and dedicated staff for achieving and maintaining the physiological rejuvenation needed for ensuring high multiplication and rooting rates.

Special mention has to be made of the mini-cutting technique developed initially in Costa Rica and then used in different Latin American countries (Murillo and Badilla, 2002; Monteuuis and Ugalde 2013; Morillo *et al.*, 2013). The shoots used as cuttings and the stock plants are both much smaller than those described previously (Monteuuis *et al.*, 1995). This system, proven to be quite efficient and attractive, requires, however, more sophisticated stock plant management and greenhouse facilities equipped with a high quality mist or fog system when shoots are rooted under aeroponics. The entire production cost of these mini-cuttings, including the facilities, has to be taken into consideration and might be a handicap compared to more conventional nursery techniques. They also will always be less efficient, more exposed to climatic constraints and requiring bigger facilities with competent staff for properly managing the stock plants than efficient tissue culture procedures (Monteuuis, 2000). Another major limitation is the impossibility to export rooted cuttings as any *in vivo* plant to foreign countries due to phytosanitary constraints, contrary to tissue-cultured plants which are by definition pathogen-free.

In Vitro Micropropagation

The easier and more efficient procedure for mass-producing teak clones in tissue-culture conditions is micropropagation by axillary budding. This is also the safest way for guaranteeing the genotypic conformity required for true-to-typeness. The protocol developed during the early 1990s in Sabah has proven to be quite adapted to the mass production of teak clones from *in vitro* germinated seeds and from teak trees of any age (Monteuuis *et al.*, 1998). Mononodal – single node – and terminal portions from vegetative shoots or 0.3 mm-long shoot apical meristems are the two types of primary explants utilized for initiating the cultures that can be sustained for several years through regular sub-cultures. The particularities of this technique including the pros and cons have been detailed (Monteuuis, 2000; Monteuuis and Ugalde, 2013). Notwithstanding a higher initial investment, the advantages of mass-propagating teak clones by tissue culture compared to more conventional nursery methods are of greater overall efficiency, especially when initiated from mature selected genotypes, using a much smaller surface area and regardless of the climatic conditions. In addition, only tissue-cultured clones, being pathogen-free, can be sent overseas across the globe and in the absence of any phytosanitary restrictions. This, and the access to superior teak clones supplied under specific conditions by a few private tissue-culture companies have accounted for the striking development of teak clonal plantations in many countries under the humid tropics over the past several years (Ugalde, 2013).

3.2.3 Current Status: Origin, Distribution and Deployment of the Clones Planted

3.2.3.1 Asia and Oceania

Notwithstanding a limited impact at the domestic level, Malaysia with YSG Biotech in Sabah and Thailand through Thai Orchids together with its subsidiary companies has played a major role in teak clone distribution all over the world. However, the genetic origin and composition of the materials supplied by Thai Orchids to Australia, Indonesia and Central America under the trade name of TOL Super Teak have never been clearly specified. Despite the fact of being tissue culture-issued, which was reported to have the miracle power of increasing its value by over 200% (see: http://www.tolusa.com/documents/TOL_Teak_Info.pdf), this material assumedly from

Northern Thailand origin turned out to be not so adapted to most of the sites where it had been planted. This could have caused the failure of Thai Orchids teak activities after some 20 years of intensive operations. Conversely, YSG Biotech, with a less dynamic marketing strategy, had placed more emphasis on genetic improvement of the species through the wise and prudent selection of mature CPTs (Goh *et al.* 2007, Goh and Monteuuis 2009). These activities have been supported and well documented by numerous scientific publications and field trials that can be visited by clients who are willing to acquire YSG Biotech clones. After more than 20 years of activities, YSG Biotech is still intensively supplying a broad variety of teak clones and genetically improved seeds from progeny/provenance trials all over the world.

Jati Jumbo/YSG Biotech clones 4 years after planting on steep slopes, Southern Java.

Figure 1

Maintenance was limited to weeding the first year, in absence of any pruning operation. The trees display the YSG Biotech TG1-8 characteristic features i.e., excellent straightness, reduced lateral branching and high leaf density accounting for increased photosynthesis and impressive growth rate. Photo: Monteuuis O.

In Indonesia, Superteak is currently considered as the best quality teak planting material for governmental teak re/afforestation projects. It is produced by Jati Unggul Nusantara "JUN" that has taken over PT Monfori Nusantara, the Indonesian subsidiary of Thai Orchids. In the absence of reliable information, it can be assumed that Superteak derives from Thai Orchids germplasm. However, this genepool has likely been improved by the enrichments from other sources such as Jati Jumbo, clonal materials from the company known as Tunas Agro Lestari (TAL), that can be easily identified based on its distinctive phenotypic features. In 2014, Superteak plants were sold at 15,000 IDR (1.14 US$) per plantable unit in plastic bag container, ex JUN nursery in Jogjarkarta. Based on farmer assessments, an average growth rate of 18 m^3/ha/yr of marketable teak wood could be expected for rotations of 5 years at 1000 trees/ha. However, the noticeable within-stand variations in yield and phenotypic traits observed for these Superteak materials prompted the users, mostly farmers, to carry out another round of plus trees selection. This had resulted in a more uniform, improved quality and cheaper material at 8,000 to 9,000 IDR (0.65 US$), depending on the quantities of plants ordered, per plantable unit in plastic bag container, from the ex Jati Utama Nasional nursery in the vicinity of Jogjarkarta. Annual yield of 20-22 m^3/ha can be expected from this Superteak improved material planted at 1000 trees/ha for 5 yr-long rotations.

Jati Jumbo turned out to be the Indonesian trade name of the YSG Biotech Solomon Island clones. On suitable sites, these clones planted in monoclonal blocks display very attractive and uniform phenotypic features (Figure 1). An average yield of at least 25 m^3/ha/yr can be expected for 1111 trees (3 x 3 m spacing)/ha after 5 years, the time at which a 50% systematic thinning must be done for allowing the remaining 555 trees to develop further. The selling price was 12,500 IDR (0.95 US$) per plantable unit in plastic bag containers ex nursery in Bogor.

Teak clones mainly from Thai orchids and YSG Biotech have been actively planted in Queensland, Eastern Australia during the early to the mid-2000s but due to changes of governmental policies, almost all the teak clonal plantations were later converted for other uses.

3.2.3.2 Latin America

Latin America is the region where teak clonal plantations have expanded the most rapidly since the early 2000s (Ugalde 2013). This was primarily due to the superiority of the clonal material acquired from YSG Biotech by a very dynamic private Brazilian company known as Bioteca before it became Proteca that specialized in mass propagation of teak by tissue culture (proteca.com.br, Goh and Monteuuis 2012, Ugalde 2013). From the beginning, Proteca had managed to develop its marketing activities to the whole of Latin America thanks to the possibility of exporting tissue-cultured plants to any foreign countries in the absence of phytosanitary restrictions as long as the shipping time is not too long. In this respect, Proteca had easier and safer access to Latin American buyers than YSG Biotech located at a far greater distance. Several millions of plantlets, mainly consisting of YSG Biotech clones, have to date been produced by Proteca, which has also developed nursery techniques for "on the spot" mass clonal production by mini-cuttings from juvenile or *in vitro*-rejuvenated genotypes (Ugalde, 2013; proteca.com.br). This option initially developed in Costa Rica (Murillo *et al.*, 2013) and whose pros and cons have been detailed elsewhere (Monteuuis and Ugalde, 2013) has been used routinely for mass producing clones selected locally or imported from abroad, at the domestic level. This has accounted for the large and uncontrolled dissemination of superior teak clones in many Latin American countries with special mention of the highly morphologically distinguishable YSG Biotech clones after they had been introduced directly from Malaysia, or via Proteca.

Since its inception in year 2000, Genfores, a Costa Rican tree improvement and gene conservation cooperative, has actively contributed to teak breeding and clone selection in close collaboration with private companies like Precious Woods, now Novel Teak, Barca, and Pan-American Woods (Murillo and Badilla, 2004; Murillo *et al.*, 2004). Initiated at the national level where 60% of the teak plants produced in Costa Rica nowadays are clones, (Murillo personal communication), Genfores expertise has benefitted an increasing number of Latin American countries including Brazil, Columbia (Espitia *et al.*, 2011), Ecuador, Nicaragua, Panama. For newly selected clones which have not been soundly field tested in operational planting conditions yet, GenFores recommends planting a sufficient number of these "candidate" clones in mixture, whereas more certified clones can be deployed in monoclonal blocks.

Teak clonal plantations are also rapidly expanding in other Central American countries like Mexico, and Guatemala, but unfortunately little is known regarding the genetic background of the clones that are massively supplied and planted there. The dramatic consequences of establishing large-scale plantations with too few clones and particularly, of questionable value, should not be minimized. And it should be kept in mind that whatever the origin, the greater the number of propagation cycles and intermediaries between the original source i.e., the CPT in situ and the operational planting, the higher the risks of mixing and losing the initial clones especially when those have been propagated or supplied as a mixture, in bulk.

3.2.3.3 Africa

Kilombero Valley Teak Company, KVTC for short, in Tanzania, East Africa is currently the biggest private teak plantation for the whole Africa. They started planting clones 12 years ago with the YSG Biotech TG1-8 (Goh and Monteuuis 2012) later enriched with locally selected materials. Out of the 8000 ha currently planted with teak, 300 ha are clonal plantations encompassing clonal tests and to a lesser extent, commercial plantations of clones in mixture. The origins of the clones are YSG Biotech (50%), KVTC own selections (40%) and various others (10%). All the different clones are individually propagated in-house by rooted cuttings (up to 100,000 per year) allowing a total control of the genetic composition of the clonal material deployed.

100 ha of teak clonal plantations consisting exclusively of a mixture of the same 8 YSG Biotech TG1-8 clones have recently been established by PFM in Gabon, Central Africa, under average rainfall of 2,500 mm/yr with a 4 month-long dry season. A clonal test comprising 32 YSG Biotech clones supplied as micro-cuttings has also been set up within the same project, to be ultimately converted into a CSO. All these clones, well identified, have been individually planted in a clonal bank.

In West Africa, large-scale clonal propagation by rooted cuttings from juvenile CSO seedlings took place in SODEFOR, Côte d'Ivoire, during the years 1995-2005 (Martin *et al.*, 2000), before applying the technology developed in Sabah (Monteuuis *et al.*, 1995) for mature selected CPTs. This technology was also proven to be successful in Forig, Ghana, and more recently in Togo, where all the 25 Plus trees selected could be cloned (Kokutse *et al.*, 2016). At SoGB, Grand Béréby, Côte d'Ivoire, 24 YSG Biotech clones have also been established within a clonal test that can be ultimately utilised as a CSO after proper thinning, the TG1-8 clones being planted between rubber tree rows as a pilot agroforestry plantation.

3.2.4 Critical Issues and Recommendations:

3.2.4.1 Genetic Background of the Planted Clones

The main risk of teak clonal forestry is the lack and loss of information regarding the genetic origin of the clones that have been mass-propagated and planted. This can be due to different reasons such as:

- The genetic background of the clone is unknown from the start;
- Inadvertent identity error or mix-up while manipulating the clones during the propagation process, setting up stock plants or during the planting operation.
- Genotype-induced differences of capacity for mass clonal propagation, especially when the vegetative procedures applied and particularly the *in vitro* protocols are not sustainably compatible with every clone requirements or particularities.
- Long-term use of bulk propagation as described earlier, where clones, which are more responsive and produce the higher numbers of shoots that can be easily rooted, will eventually supplant the others.
- Marketing strategies for clones supplied in mixture like the Malaysian Solomon clones, without revealing the accurate quantity and identity of the genotypes, or referring only to the country they are coming from. This kind of information is too vague and imprecise as the same clones can be found in various countries. Consequently clones assumed to be different as imported from different places or suppliers may actually be the same.

The threat is a rapid impoverishment of the genetic diversity of the clones deployed for large-scale planting, exposing them to greater risks of pest and disease problems and ultimately of a too high uniformity of the end-use products.

This is why maintaining wise genetic improvement programs aiming at producing new clones is crucial (Monteuuis and Goh, 2005). The different clones introduced recently in trials by PFM in Gabon and SoGB in

Côte d'Ivoire with their eventual conversion to CSOs are a good illustration of what can be done in this respect.

Noteworthy is also the sound utilization of adapted DNA markers that can be very helpful for overcoming genetic origin and relatedness issues (Monteuuis and Ugalde, 2013), but unfortunately these technologies are currently still underused especially at the operational level.

3.2.4.2 Planting Site

Precipitations appear to be of great importance. As long as they are well drained and not prone to waterlogging, planting sites exposed to high and well distributed rainfall regime – 2000 mm/yr or more – are recommended to get the earliest returns on investments for superior teak clones which are usually more expensive than unselected seedlings. Conversely, long dry periods have been observed to promote lateral branching of certain clones, depreciating their log quality even if the volume of wood produced remains superior to what can be obtained from other origins (Monteuuis and Goh 2012). Further, soil acidity has apparently less influence on teak development (Chaix *et al.*, 2011, Monteuuis *et al.*, 2011, Goh *et al.*, 2013).

3.2.4.3 Clone Deployment

Clones can be used for establishing monospecific plantations, but also to be intercropped with other species of a different kind within agroforestry systems or even for silvopastoralism.

Clones for monospecific plantations can be mixed with seedlings or are usually planted in mixture as a bulk with the purpose of minimizing the negative impact of unadapted genotypes as compared to monoclonal blocks which are more uniform, for better or worse. Such mixtures can be warranted as most of the clones are not tested in the conditions of large-scale deployment prior to their utilisation owing to time, space and cost reasons. In addition, intercropping clones with seedlings diminishes planting stock cost, seedlings being cheaper than cutting or microcutting-derived clonal material. On the other hand, selected clones, contrary to seedlings, do not require intensive thinning operations for removing the poorest trees and thus can be planted at a lower density, compensating at least to some extent for their higher cost.

Silvicultural practices consisting in harvesting several times from the same stump, taking advantage of teak specific coppicing ability for avoiding replanting have been undertaken, but were apparently not as successful as expected (Martin *et al.*, 2000, 1999). Similarly to industrial eucalyptus plantations, the best way of deploying teak clones proven to be adapted to the local conditions is in the form of monoclonal blocks established according to a space-time mosaic design. The intention is to avoid overly large areas planted with genetically related clones which are more susceptible to potential pest and disease damages. The size of these monoclonal blocks will depend on the total number of clones, their genetic relatedness, their individual phenotypic characteristics, the rotation length and the total area to be planted.

Teak clones can also be selected on trunk shape and crown form criteria to be intercropped with other fruit or vegetable species within highly productive agroforestry systems, benefiting from the culture conditions provided to the other crops for a higher return than could be obtained from seed-issued trees.

Finally, teak clones due to their higher vigour, stronger root systems and attractive phenotypic features have been observed to be more suitable and economically profitable for silvopasture than seedlings (Ugalde, 2013).

3.2.5 Concluding Remarks

For teak, the high-value tropical timber species that has been the most planted worldwide, clonal forestry has demonstrated its capacity to overcome most of the limitations associated with seedling-derived plantations. It is now possible to establish fast growing and uniform teak clonal stands of enhanced yields, high wood quality and commercial value on short rotations. The clonal option appears to be the best way to maximise returns on investments for the establishment of monospecific or mixed teak plantations. Teak clonal forestry can thus become a success story providing outstanding genotypes that can be wisely and reliably selected to be mass clonally multiplied using appropriate methods before sound deployment on suitable planting sites.

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CHAPTER 4
Natural Teak Forests – Silviculture and Stand Management

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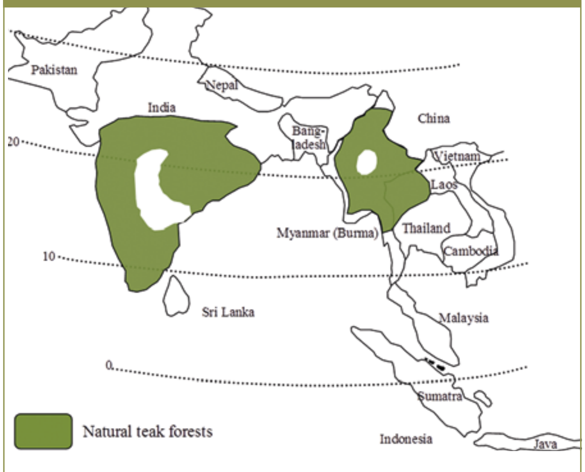
4.1 Natural Teak Forests

Teak naturally occurs in four South and Southeast Asian countries, namely Myanmar, India, Lao PDR and Thailand (Figure 1). In 2010, the total area of natural teak forest in the aforementioned countries was estimated at about 29 million hectares and almost half of the total teak forest areas can be found in Myanmar (Kollert and Cherubini 2012). These four countries have practiced similar silvicultural systems on natural teak forests, depending on the forest types and site conditions. The earliest system of managing natural teak forests in these countries was the selection system: a given forest area was worked under predetermined felling cycle, minimum girth, and remaining mother trees as seed bearers to ensure natural regeneration of teak forests. The selection system aims at harvesting mature and over-mature trees across the entire forest area by preventing formation of large canopy openings in the long-term view. Theoretically, the system retains continuous forest cover while assuring soil fertility, maintains the unique floristic composition and uneven-aged structure of forest stands, and encourages resistance against pest and diseases (Bebarta, 2002). However, the area and growing stock of natural teak forests in their natural habitat have been gradually decreased for several reasons.

In Myanmar it is obvious that the teak forests are declining due to logging (legal and illegal), agricultural expansion, shifting cultivation, and mining, etc., with an annual deforestation rate of 0.9% (FAO and RECOFTC, 2016). In India, natural teak forest degradation is accelerated by over-exploitation for local uses (Tewari, 1992) and livestock grazing. In the case of Laos the teak forest area and growing stocks decreased due to population pressure, shifting cultivation, and forest fires (Anonymous 1998). The natural teak forests in Thailand decreased with economic growth, agricultural expansion, encroachment, illegal logging, shifting cultivation, and fires, etc (Sumantakul and Sangkul 1998; FAO and RECOFTC 2016). Nowadays, an assessment of the silvicultural system

Distribution of natural teak forests Figure 1



Source: Gyi and Tint, 1998

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is applied in natural teak forests; whether the system has been perfectly and sufficiently applied in the prescribed silvicultural operations, is crucial for improving the system and an evaluation of the performance of the system by investigating the regeneration status of desirable species in the logged forests.

4.1.1 Myanmar

In Myanmar natural teak-bearing forests are distributed between the Northern limit of 25° 30' N and the southern limit of 15° and 16° N, while it extends beyond the boundaries of the Shan State in the East and to the Rahkhine State in the Western watershed of the Ayeyarwady and Chindwin rivers (Troup 1921). However, they do not occur in both the Central dry zone and in the tidal regions of the delta area, or in areas of more than 914 m above sea level. The forests in Myanmar are categorized into six major forest types and teak generally grows in semi-evergreen forests, mixed deciduous forests and deciduous dipterocarp forests. Among these forests, the best quality of teak trees grows in mixed deciduous forests with cleaner and straighter boles (Kermode, 1964; Myint, 2012). According to the 2010 teak resources assessment (Kollert and Cherubini 2012), the area of natural teak-bearing forests decreased from 14,600,000 hectares in 1976-1979 to 13,479,000 hectares in 2010. Nevertheless, Myanmar still possesses more than half of the total growing areas of teak. In 2014, Myanmar introduced a timber export ban on round logs; followed by a temporary logging ban in the country and a 10-year logging ban in the home of teak-bearing forests, in Bago Yoma, to conserve and protect the natural teak forests (Figure 2).

Figure 2

Natural teak forest in Myanmar
Source: Forest Department, Ministry of Natural Resources and Environmental Conservation

4.1.2 India

India is the largest country in South Asia with more than 70% of the total landmass of the region and is located between latitudes 8° N and 37° N and longitudes 68° 7' E and 97° 2' E. The elevation varies, ranging from an average elevation of 6000 meters above sea level in the mountainous region to 30 meters above sea level in the coastal areas. India has diversified climatic conditions, ranging from tropical wet to semi-arid and arid (Pant and Kumar, 1997, Ghassemi and White, 2007). The average annual temperature is varying from the Himalayas to the arid and semi-arid areas, with a temperature range of 5 °C to 40 °C in the hottest month and of 0 °C to 30 °C in the coldest month (Hussain, 2008). The humid North-East (North-Eastern India, Sikkim and North-Western West Bengal) receives the highest annual rainfall, i.e. 200 cm, and the arid region receives the lowest annual rainfall of less than 25 cm.

India is the second largest populous nation in the world, with about 1.25 billion people in 2011 (Visaria and Ved 2016). There are 14 forest types in India, of which the subtropical dry deciduous, tropical moist deciduous, tropical thorn and tropical wet evergreen forests are important (Rawat and Ginwal 2009). Teak naturally grows in regions below 24° N latitude and natural teak forests covered about 6,810,000 hectare in 2010. Apart from Kerala, Tamil Nadu and parts of Maharashtra where artificial regeneration is applied, natural regeneration is the main tending practice in most parts of natural teak growing areas. Other silvicultural systems such as the coppice system, clear felling with conversion to uniform system, and the selection system with improvement felling are also applied in natural teak forests (Kumaravelu, 1991). Although the Indian forests were managed as an open access resource until the end of 1800, the Forest Act enacted in 1865 encouraged the state acquisition of forests (Haeuber, 1993). The earliest attempts to manage the natural forests of teak in India consisted of securing a sustainable supply of timber. In 1880, the rulers of India paid special attention to teak forests for providing quality wood for the navy and ship-building industry (Negi, 1994). In 1980, India imposed a timber export ban on logs and lumber (Bourke, 1988).

4.1.3 Lao PDR

Laos is situated between latitude 13º 54' N and 22º 30' N and longitude 100º 5' E and 107º 59' E. The elevation in Laos varies from the mountains to the plateaus, while the average height of the mountains is about 1500 meters above sea level. Laos experiences monsoon climate. The annual rainfall ranges from 1000 mm in the North to 3000 mm in the South. The average annual temperature is in the range of 10 °C in January to 38 °C in July. However, temperatures rise up to 40 °C in the hot season before the monsoon comes (Stuart-Fox, 2008). In 1999, Laos had a population of approximately 5 million people, of which 90% relied on natural resources for their subsistence living (Poffenberger, 1999).

The forests of Laos can be subdivided into 9 different forest types. Teak forest forms part of the mixed deciduous forest in the Southern area. Teak occurs naturally in the northwest provinces that continue from natural teak forests of Myanmar and Thailand (Pengduoang, 1991). The teak forests in Laos are considered the Eastern boundary of teak natural distribution (White, 1991; Perry, 2007). Teak occurs in the moist deciduous forests in Sayabouli and Bokeo Province, covering an area of 10,000 to 20,000 ha in the former and small areas in the latter (Cairns, 2007). The selection system was used to manage natural teak forests of Laos in the past (Pengduoang, 1991). The area of natural teak forest declined substantially between the period of 1976 and 2010 – from 70,000 ha in 1976 to 15,000 (Kollert and Cherubini, 2012) ha in 2010. A temporary teak logging ban was imposed in 1991 (Cranmer *et al.*, 2002).

4.1.4 Thailand

Thailand is a tropical country located in Southeast Asia and is well-endowed with a variety of natural ecosystems and cultures. Thailand is situated between Northern latitudes 5°37’ and 20°30’ and Eastern longitudes 97°20’ and 105°39’. The country’s total land area amounts to 514,100 km^2 with an elevation of 2590 meters above sea level. The country experiences monsoon climate with an annual rainfall ranging from 1000 to 4000 mm. The average annual temperature is about 25 °C, while dry season temperature is as high as 40 °C and winter season temperature is as low as 0 °C. The country’s total population is approximately 63 million inhabitants with a population density of 123 persons per km^2 (FAO 2009). Of the country’s total population about 80% reside in rural areas.

The forests in Thailand are classified into two main types, evergreen and deciduous forests. The former is further divided into tropical evergreen forest, pine forest, mangrove forest and beach forest. Natural teak forests occur within a latitudinal range of 16° to 20°N and a longitudinal range of 97° to 101°E. Then distribution and silvicultural systems of natural teak forests are similar to those in Lao PDR and Myanmar. Teak trees occur mainly in mixed deciduous forests throughout the northern part of the country (Kaosa-ard, 1991) and covered about 8,744,000 hectares in 2010. Teak forests have been managed under the Brandis Selection System since 1896, but teak logging has been banned since 1989 (Pragtong 2000). As a silvicultural system, improvement felling is solely practiced in natural teak forests.

4.2 Status of Natural Teak Forests in Myanmar

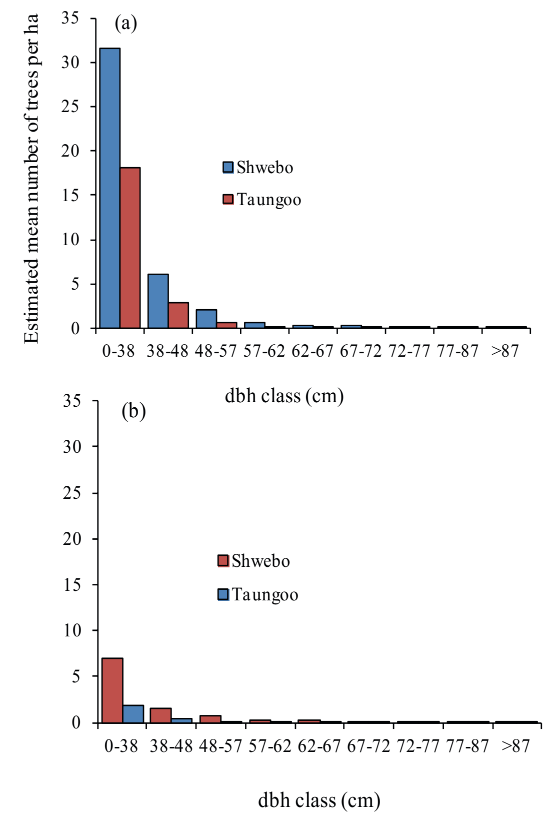
4.2.1 Natural Teak Forest Growing Stocks and Stand Structure

The growing stock of teak showed a downward trend in Myanmar, and was reduced from 107 million m^3 in 1990, 104 million m^3 in 2000, and 100 million m^3 in 2005 to 87 million m^3 in 2010 (FRA, 2015). Diameter distributions of teak and associated species in the natural teak bearing forests according to the National Forest Inventory carried out by the Forest Department, Ministry of Natural Resources and Environmental Conservation during 2013-2014 in Taungoo and 2014-2015 in Shwebo districts are provided in Figure 3a and b and Figure 4. The inventory covered a total area of about 308,982 ha in Taungoo and 1,495,034 ha in Shwebo. The stand curves above 39 cm dbh for teak and associated species are unsatisfactory in all of the aforementioned inventory areas.

If the profitable extraction of volume is considered to be 17.5 m^3/ha (Tint, 2015), the numbers of pole size trees for teak and associated species are inadequate for creating the next rotational crop. According to Win‘s (2013) findings, who worked on the effect of selective logging on forest stand structure and natural regeneration, profuse regeneration of teak occurred on logging road and log yards nine months after logging. However, about half of these regenerations disappeared after 34 months when the undergrowth, bamboo seedlings in particular and weeds in general, occupied the logging roads and log yards. This also indicates the need of timely implementation of the prescribed silvicultural operations under the Myanmar Selection System.

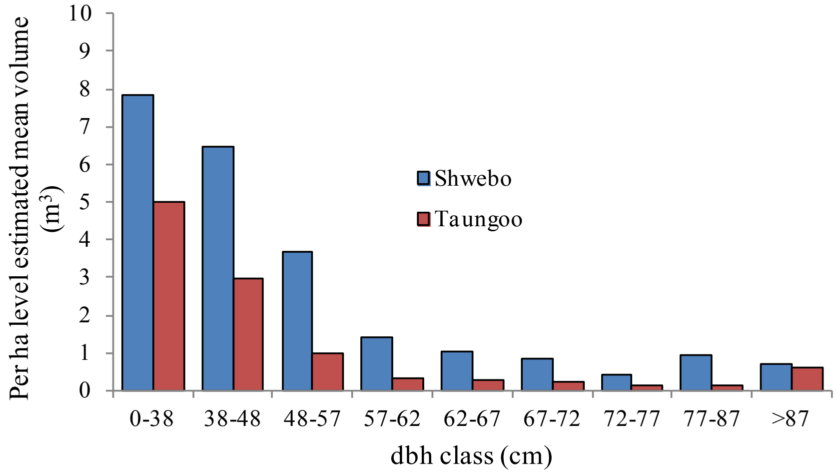
Figure 3

(a) Stand structure of teak and associated species and (b) stand structure of teak in natural forests based on preliminary NFI in 2013-2015.



Estimated mean volume (m³/ha) of teak and associated species in natural teak forest of Myanmar based on preliminary NFI in 2013-2015

Figure 4



4.2.2 Site Influence on the Stand Structure

Stand structure of natural teak forests reflects the interaction between vegetation growth habit and environmental conditions, management practices, and natural or human disturbances. In addition, the quantitative information on stand structure is intimately related to silvicultural and management decisions (Van Laar and Akca, 1997). However, site conditions have a significant influence on the stand structure of natural teak forests. Although teak thrives on a variety of soils and geological formations, it grows best under full overhead lights on good drainage subsoil and suitable growing space for proper development. Teak grows in pure stand on well-drained deep alluvial soils and shows better development on gentle slopes of fertile soils.

As a rule, teak grows in association with *Xylia xylocarpa*, *Pterocarpus macrocarpus*, *Terminalia tomentosa*, *Dipterocarpus alatus*, *Cephalostachyum pergracile*, and *Bambusa tulda* in the moist mixed deciduous teak forest. In the dry mixed deciduous teak forest teak occurs with co-occurring species such as *Xylia xylocarpa*, *Terminalia tomentosa*, *Homalium tomentosum*, *Shorea obtusa*, *Shorea siamensis*, and *Dendrocalamus strictus* (Troup, 1921). Teak occurs in relatively small proportions in natural teak-bearing forests in Myanmar with considerable representation of teak composition ranging from 15-33% for sound teak trees 3 ft in girth and over (Troup, 1921). Saing Reserve Forest in Taungoo is the poorest forest, in which teak represents the lowest percentage, i.e., 6%, for sound teak trees 3 ft in girth and over (Troup, 1921). The stand structures of teak are shown in Figure 5, based on Nyi Nyi Kyaw's (2003) findings in Taungoo, Mabein, and Kanbalu.

The natural teak forest in Taungoo occurs in moist deciduous forests along the hill (Moist Upper Mixed Deciduous forest – MUMD), teak forest in Mabein grows in the moist forest type on flat plains (Lower Moist Deciduous forest – LMD), while teak forest in Kanbalu thrives in dry mixed deciduous forest. The stand structure of teak forests in Kanbalu and Mabein exhibited a normal stand structure with a higher number of small trees in the lower diameter classes and sloping down as the diameter increases (Figure 6). The stand structure of teak forest in Taungoo showed lower numbers of trees in smaller diameter classes, indicating that the yield cannot be sustainable and will drop in the following felling cycles. The height-diameter curves fitted by Prodan's model indicated that the stands in Taungoo and Mabein were in a dominant position while the stand structure of the latter reflected the mature stand condition (Figure 5). The total tree heights were ranked in order of Taungoo > Mabein > Kanbalu with the tallest trees attaining the height of 45 m, 35 m and 30 m in each stand. The natural teak forest in Mabein also had the highest number of tree species and the highest tree density.

In the upper canopy, remarkable proportions of teak trees with ≥ 10 cm dbh were found in Mabein, i.e., 68% of total growing stocks, followed by Taungoo, in which teak amounted to 67%. In the upper canopy of a natural teak forest in Kanbalu, teak occupied about 36% of the total growing stocks. These valuable results indicated that teak in the moist deciduous forests attained the dominant position with the highest teak density, indicating genetic diversification of teak. Hence, quantitative analysis of forest stand structure and floristic composition provide information on potential sites for genetic conservation of teak resources.

4.3 Stand Management of Natural Teak Forests

4.3.1 Myanmar

Systematic forest management was initiated in Myanmar and mainly based on natural teak forests with the main target of sustained teak extraction. Therefore, the system was known as 'sustained yield management

Figure 5

Stand height curves of teak trees with ≥10 cm dbh in the investigated stands [adapted from Nyi Nyi Kyaw (2003)].

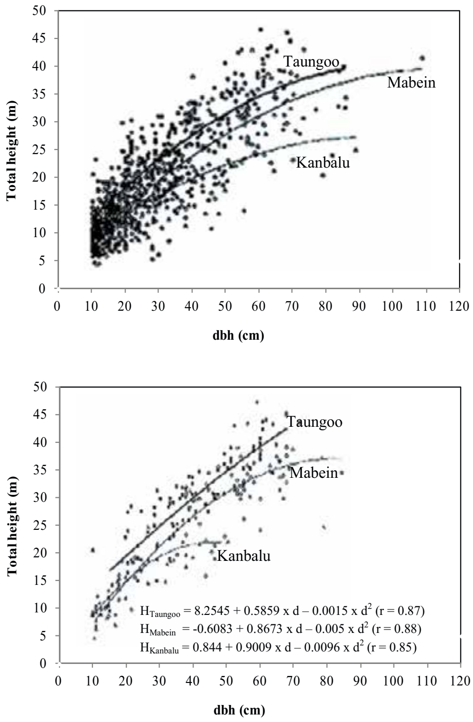
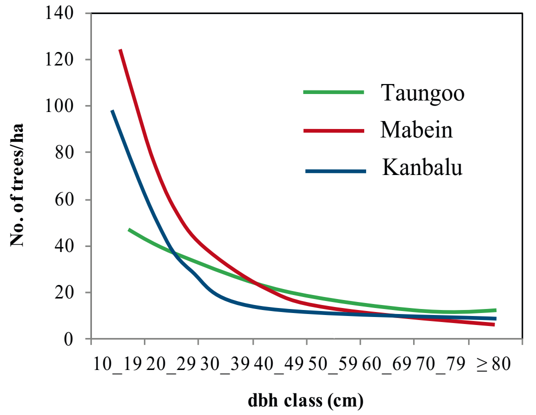


Figure 6

Stand structures of teak in natural forests [adapted from Nyi Nyi Kyaw (2003)].



system' as well as 'Brandis Selection System' because it had been initiated by Dr. Dietrich Brandis in 1856 (Gyi and Tint 1995; Zin, 2005). This was the first attempt of managing tropical forests on a scientific basis and proved fundamental for the development of future tropical forest management in the tropics (Zin, 2005). The Brandis Selection System is one of the world's oldest silvicultural systems in tropical forestry (Perry, 2007). Under the selection system, the growth and development of valuable species are enhanced through the felling of undesirable tree species (Rawat, 1993). As the system is a form of selection-cum-improvement system (McDermott, 1988) with the intention of carefully protecting immature stock and assisting young teak trees to attain maturity (Blanford, 1956; Kyaw, 2004), teak trees are treated with cultural operations such as weeding, removal of climbers, defected and unsound trees, etc., and harvested selectively in a given forest area (Perry, 2007). Nonetheless, the Brandis Selection System favours teak trees. Therefore in 1920 the Brandis Selection System was modified into 'Myanmar Selection System (MSS)' to include associated hardwood species. The silvicultural operations under MSS are Selection-Felling (SF) marking of marketable species including teak, enumeration of residual trees, improvement felling, thinning and cleaning, extraction, enrichment planting and fire protection.

The main objective of MSS is to maintain sustainable yield of natural forest by reaping only the annual increment over the entire forests while leaving the growing stock intact. Therefore, careful enumeration of residual trees – all teak trees ≥ 39 cm dbh and all commercial trees below 10 cm of exploitable dbh – are crucial for estimating the future yield over the next felling cycles. In degraded forest areas after over-exploitation with scarce teak mother trees, enrichment planting by sowing of seeds or stump planting in line or patch pattern are carried out. A summary of the silvicultural management of natural teak forests is given in Box 1.

Under the selection system, a number of cultural operations such as improvement fellings, natural regeneration fellings, thinning operations in natural regeneration of

Box 1

Silvicultural Management of Natural Teak Forests in Myanmar

The Myanmar Selection System was adopted in the moist and dry mixed deciduous forests of Myanmar. The MSS consists of the division of 30 blocks of equal yield capacity; selective logging is carried out in each of these blocks every year. The minimum exploitable girth limit is 229 cm (7.5 ft) for moist deciduous forests, while the girth limit for the dry mixed deciduous forests is 198 cm (6.5 ft).

Under the MSS, seed bearers are maintained to ensure natural regeneration of teak forests. In addition, the two cultural operations, namely: "O Felling"– improvement felling in favor of young teak trees before harvesting and "Y Felling"– cultural operations in favor of growth and development of natural regeneration after selective logging, are applied.

teak, climber cuttings, fire protection and natural regeneration by Taungya have been carried out to encourage and improve teak natural regenerations (Keh and Aung 1995), as well as to maintain sustainable production of high quality teak. However, with a long history – of more than 150 years (1856-2016) – of application of the Myanmar Selection System, these silvicultural treatments have not been sufficiently applied in all natural teak forests, and, thus, sustained-yield management according to the Myanmar Selection System has not been realized in natural teak forests of Myanmar. Quantitative harvesting of high quality teak results in creaming of natural teak forests (Tint, 2015) frequently leaving behind an insufficient number of seed bearers, thus the sustainability of natural teak-bearing forests and conservation of teak genetic diversity is in question.

4.3.2 India

Dietrich Brandis, the first Inspector General of Forests, initiated systematic forest management in India and working plans in many areas (Negi, 1994). Although the working plans had covered about 282 km^2 by the end of 1885, by the end of 1965 they covered approximately all of the reserved forests in India. During the first quarter of the 20th century, the scientific management of forests was paid great attention to and management plans including Working Plans, Intensive Forest Management Plans, and Working Schemes covered almost all of the reserved and protected forests. However, during the World Wars, the scientific management of teak forests was ignored resulting in over-exploitation of the forests in order to meet the growing demand by the rulers (Negi, 1996).

In the post-independence period, the two systems, clear felling-cum-selection-cum-improvement system, and selection and improvement systems, were implemented to encourage natural regeneration of teak forests, which had been over-logged in the past. By the late 1980s, deforestation was taking place at a considerable rate. During the period of 1980-82, the forests in India covered about 14.1% of the total land area and closed forest cover continued decreasing until the last decade (Haeuber, 1993). From 1983-1987, the deforestation rate was 47500 hectares per year (Negi, 1996). The silvicultural management of natural teak forests in India is given in Box 2.

For the first time in the post-independence period, in 1988 the State affirmed that management of forests not only contributed to the environment and soil conservation but also provided for the subsistence needs of the local communities (Arora, 1994). Since then, Joint Forest Management has been initiated by Orissa State to encourage people's participation in forest protection and in the development of forests. Later, it was realized that people's participation in forest protection could become the most cost-effective way in managing the forests (Arora, 1994).

Box 2

Silvicultural Management of Natural Teak Forests in India

Dietrich Brandis initiated scientific forest management and the Brandis Selection System in India in the late 19th century. The selection system was practiced in the tropical mixed forests characterised by a low composition of economically valuable species and poor accessibility, with less information on end uses of most species and the need to protect the environment, (Nair and Chundamannil, 1985). The selection system was adopted in the moist mixed teak forests of Raipour, Rajnandgaon, Balaghat, Seoni, Chinawara, Betul, Hosangabad (Bebarta, 2002), Andhra Pradesh and Maharashtra (Nair and Chundamannil 1985) with the prescription of a 20-40 yr felling cycle and exploitable girth limit of 60-120 cm. In the dry teak forests of Orissa including the Kalahandi, Bolangir, Rayaganda, and Jaypore Forest Division, the selection system was practiced with an area method of yield regulation.

At the present time, dry deciduous teak forests in Bihar, Gujarat and Maharshtra are managed under the coppice with reserve systems with a 20-40 year coppice rotation, while moist teak forests are managed by using selection and improvement systems (Negi, 1996). There was no evidence on sustained yield production in the moist and dry mixed teak forests in India. The natural regeneration of most valuable species was not ensured and the canopies opened during the felling operations rarely encouraged natural regeneration.

4.3.3 Lao PDR

Under the selection system, the mature and marketable defective trees are harvested with a volume control method of yield regulation: harvesting of 25 cm^3/ha or more in a 50-year felling cycle (Anon, 2001). The management plans that covered only 1% of Lao's forest areas were carried out under a selection system in 1959 (Perry, 2007). These days, timber harvesting consists of left-over logs from the previous felling and shifting cultivation areas and the Department of Forestry is responsible for controlling teak trees to be felled. The exploitation of teak forests is not carried out every year (FAO, 2009). Commercial harvesting of forests is conducted based on the quotas described by the Ministry of Finance and the Office of the Prime Minister (FAO, 2009). In 1991, participatory forest management was initiated by instituting a land and forest allocation (LFA) law giving permission to the village to manage forests within the village boundary (Inoue, 2013). However, LFA is not the best solution for sustainable forest management via a participatory forest management approach (Fujita and Phengsopha, 2008).

4.3.4 Thailand

Early forest management was custodial and local fiefdoms managed the forests, primarily for domestic use and export through European companies. In 1896, the Royal Forest Department (FRD) was established to manage forests in Northern Thailand (FAO, 2009; Pragtong, 2000; Myllyntaus and Saikku, 2001) as well as to collect revenue from the Teak forests (Myllyntaus and Saikku 2001), and thus, the RFD became the initiator of forestry legislation. In parallel with the establishment of RFD, Thailand introduced the Burmese Selection System (FAO, 1958; Gyi and Tint 1995; Collins *et al.*, 1991; Johnson and Durst, 1997) as forest management strategy under its forestry programmes. In 1899, the forest land ownership and governance had shifted toward the Government. For more than five decades (1896 to 1950s), the RFD was solely responsible for commercial timber extraction and taxation of teak forests in Thailand. The silvicultural management of natural teak forests in Thailand is given in Box 3.

In 1947, the Forest Industry Organization (FIO), an off-shoot of the RFD as public forest enterprise for managing forest and timber extraction, was established (Pragtong, 2000; Desai, 1998). In 1956, the FIO was separated from the RFD and reformed as an agency (Desai, 1998) in order to control forest industries and Provincial Logging Companies (Poore, 1989; Myllyntaus and Saikku 2001). After reorganizing the FIO, as a state agency the FIO controlled largely timber extraction, teak plantation establishment, Thai Plywood Company, and logging companies. Later, in 1962, national parks' management, conservation, and forest gazetting became the main tasks of the RFD. Since World War II, the government promoted extensive forest exploitation to encourage the forest industry. From 1969 to 1979, about 516 timber concessions were granted logging operations and they covered approximately half of the country's total land area. In addition, migration of local communities into the logged-over forests, shifting cultivation and clearance of forest land to avoid post-war communist insurgency led to an overexploitation of forests, and as a consequence deforestation accelerated. In 1989 Thailand imposed a logging ban because of the severe floods and landslides encountered in the South in 1988 (Pragtong, 2000) combined with an increasing public awareness of environmental conservation. After imposing the logging ban in 1989, the management of natural forests put an emphasis on the remaining forest areas, consisting of protected areas and national parks as well as production forests (Sumantakul and Sangkul 1998), for conservation and protection purposes (Waggener, 2001). Thus, teak plantation management has received increasing attention.

Box 3

Silvicultural Management of Natural Teak Forests in Thailand

The Brandis Selection System developed by Dietrich Brandis in the late 19th century in India, was first introduced in Thailand in 1896 (FAO, 1958; Gyi and Tint 1995; Collins, 1991; Johnson and Durst 1997). In 1939, the selection system was modified with the prescription of a 30-year-felling cycle (Phānitchaphat, 1962) and a girth limit of 213 cm. At the initial stage of system implementation, teak forest was divided into two blocks - logging and non-logging block. The former was further divided into 5 compartments and 3 felling series plots to work under 15-year-logging operations and concession. Later, in 1953, teak forest was divided into 40 working plan units; in each unit 30 felling series were drawn to work with a 30-year logging concession. Exploitation of teak forest was carried out based on yield regulation according to the principles of the Brandis Selection System.

Pre-harvesting inventories were conducted in Thailand, especially for yield calculation. The RFD was responsible for marking teak trees to be felled and prescribing the felling direction. The introduction of a selection system was mainly for yield calculation and to control timber extraction in Northern Thailand, and, thus, the production forests were determined and selected based on the requirements of the concessionaires (Poore, 1989). Therefore, commercial timber extraction hit the highest point after granting a 30-year logging concession for the first time. During the period of 1969 to 1979, there were about 516 timber concessions granted with logging a operation of approximately half of the country's total land area (Bryant, 1997).

4.3.5 The Future of Natural Teak Forests

Teak is one of the most well-known and valuable premium hardwood species globally and native to Myanmar, India, Laos and Thailand. Natural teak forests cover an area of 29 million hectares, of which approximately half of the total growing stock is in Myanmar (FAO, 2012). The Brandis Selection System is the first attempt of managing tropical forests on a scientific basis and it has been implemented in natural teak forests for several decades. Nevertheless, the areas of natural teak forest declined substantially in all teak native countries due mainly to logging (legal and illegal), agricultural expansion, shifting cultivation, population pressure, and grazing, etc. In addition, mass production of high quality teak results in creaming of natural teak forests, and, thus, status of seed bearers and natural regeneration are not ensured; sustainability of natural teak-bearing forests and conservation of teak genetic diversity are in question. Gyi and Tint (1998) state the decline of natural teak forests was not due to the weakness of the management system used in these forests but to the overharvesting and insufficient application of standard silvicultural operations prescribed in the system itself. In addition, the failure of systematic management in a sustainable way under selection systems is influenced by complex social, political, cultural, ecological dimensions, and many constraints which are far beyond the control of the forestry sector.

Insufficient implementation of standard silvicultural operations has been recognized as the basis of inadequate natural regeneration. As the intention of managing forest is to maintain sustainable production of timber to continuously support the increasing demands and ever-changing needs (Appanah, 2013), the selection system needs to consider sustainability of timber production, impacts of logging operations, adequacy of natural regeneration, as well as the social-welfare of local communities. As an attempt to protect and conserve the remaining natural teak forests, a logging ban was imposed in the early 20th century in India, Laos, and Thailand. Participatory forest management was introduced to include local communities in forest governance and paid more attention to teak plantation. However, sustainable management of natural teak forests through participatory management is still facing the constraint and challenges (Fujita and Phengsopha 2008). It is obvious that forest degradation has continuously taken place since participatory forest management was first introduced in the 20th century.

According to the FAO's 2012 report, degradation of natural teak forests is a global concern and the natural teak forest covers in all teak native countries gradually decreased between 1992 and 2010, with the exception of Thailand. In Thailand, a complete logging ban in natural forests was introduced in 1989 and this may have encouraged the recovery of natural teak forests, which are reported to have increased by 2.9 million ha. The increase in teak forest area in Thailand is a good example of improving recovery of natural teak forests.

4.4 Recommendations

A combination of various factors such as the application of proper silvicultural operations, encouraging participatory forest management approaches and strengthening good governance to combat illegal logging on one side and establishment of forest plantation through the use of high quality planting materials to supply demands on the other side can contribute to the recovery and sustainability of natural teak forests. The following options are recommended for the effective management and sustainability of natural teak forests as well as the conservation of teak genetic diversity:

- Investigate the silvicultural systems that are applied in natural teak forests for determining the needs to improve the system and evaluating the performance of the system through the investigation of regeneration status of desirable species in the logged forests.
- Strengthen forest governance to combat illegal logging into the natural teak forests.
- Encourage participatory forest management for sustainable management of natural teak forests.

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CHAPTER 5
Planted Teak Forests

5.1 Establishment and Management of Planted Teak Forests

Mauricio Jerez-Rico[15] and Sylvio de Andrade Coutinho[16]

5.1.1 Introduction

Teak (*Tectona grandis* L.f.) is the worldwide foremost tropical precious hardwood. It was introduced in Java in the 14th century and Sri Lanka in 1680. Large scale plantations began in India in the first half of 19th century, and were introduced in Africa and America just before the beginning of the 20th century (Evans, 2009). Today, teak is planted in more than 60 countries with tropical/subtropical climate. Substantial progress has been accomplished in the establishment and management of teak plantations: improvement of vegetative material, site selection, soil preparation, planting and tending, density management, harvest operations, and wood utilization. Nevertheless, it is necessary to fully adopt modern management techniques to increase the productivity of existing and new plantations to ensure the supply of high quality timber to satisfy the increasing demand from the markets. At the same time, in the face of climate change and emerging environmental concerns, teak management must address issues such as biodiversity, carbon sequestration, and water conservation. New approaches, concepts, and tools have been adopted already for intensively managed plantations (e.g., eucalyptus) resulting in large increases in productivity. Establishing and managing teak plantations must be considered as an integrated silvicultural system, rather than a set of separated operations (e.g., soil management and stocking), and an interdisciplinary approach integrating several disciplines (e.g., precision forestry, and marketing strategy) is needed. There is a growing body of knowledge on teak management. Lately, two comprehensive works on teak management have been published: (Camino & Morales, 2013) – in Spanish –, with experiences from Latin America) and (Ugalde, 2013) – in English – exploring experiences from all over world. Besides, several reports and proceedings of meetings on the subject have been published by IUFRO, FAO, and ITTO (e.g., Kollert & Cherubini, 2012; Bhat *et al.*, 2005). Over the last five years a considerable number of papers, reports, and books have appeared, offering new insights on many aspects of teak cultivation.

In this Chapter, our focus is chiefly on the establishment and management of even-aged commercial teak plantations, across Asia/Oceania, Africa, and Latin America, aimed at producing solid wood products in the context of Sustainable Forest Management and Intensive Forest Management. In view of the broad scope of the subject, only some key issues are addressed in some depth: site selection, soil and nutrient management, standing stock regulation, and rotation age trends. Natural hazards are summarized, including fire risks, pest outbreaks, as well as climate change-related events such as strong winds and chronic or extreme drought-entailing significant risks for teak plantations. Finally, we synthesize the findings in a set of learned lessons and suggested policies aimed to improve sustainable forest management in teak plantations.

5.1.2 Silviculture for the Establishment and Management of Planted Teak Forests

The establishment and management (E&M) of teak plantations is not an isolated task; many other activities must be carefully planned and executed before the establishment considering their interdependence (see Figure 1).

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Carrying them out as isolated operations might result in poor results or failure. Moreover, financial considerations are crucial for the whole process. Activities include previous operations: site selection, choice of the best genetic material for planting (seed, seedlings, clones), and good systems of seedling production to ensure high quality material for planting. On selected sites, it is necessary to delimit the effective planting land, and to build roads including firebreaks to facilitate permanent access to the stand.

Throughout the establishment phase, the goal is to ensure good plant survival towards canopy closure. The selection of the initial spacing is the first critical activity, as it determines future standing stock management, plant production needs, and soil preparation operations. Land cleaning depends on the type of previously existing vegetation. Burning is being abandoned as a practice of land cleaning, and today mechanised or chemical cleaning predominates. Soil preparation aims at creating optimal conditions for plant growth and comprises specific activities depending on site/soil specific characteristics. Planting, weed control, singling, and eventually replanting are important activities in this phase. Weed control is essential, as teak does not tolerate competition for light, water, and nutrients. Especially damaging are vines. Control techniques vary from manual to mechanized and chemical. The method depends on the scale of the project, available technology, workforce, and environmental regulations. The objective in the management phase is to regulate tree competition, and ensure that the best trees (in terms of desired products) reach the final harvest. The main activities are thinning prescriptions to reduce tree competition and to discard low quality trees, and pruning to improve stem and wood quality. Nutrient management comprises activities such as liming, fertilizing, and soil management practices to meet the species´ nutrient requirements by enhancing soil fertility and minimizing soil degradation).

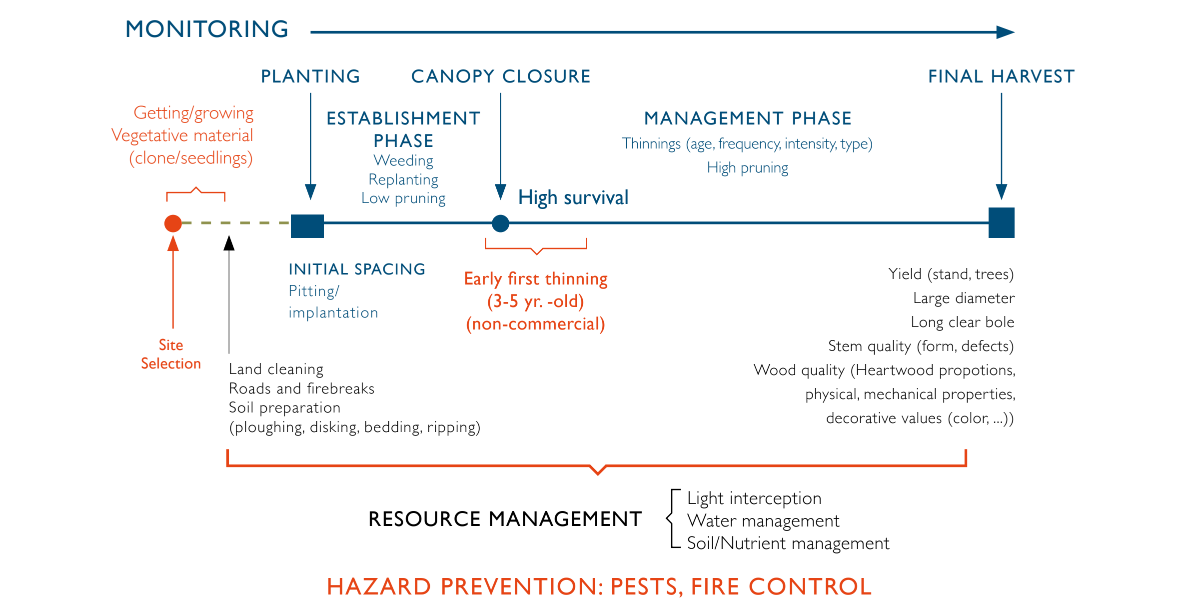
Adequate hazard prevention plans and control are necessary throughout the rotation, especially for fire, pests and diseases. A good monitoring plan is essential to ensure the timely and appropriate execution of activities and for the meeting of expected growth and yield goals. The timely execution of several E&M activities is critical. For example, planting too early or too late can lead to low survival, poor growth, or even total loss. In Brazil, where the best time for planting is within the first half of the rainy season, a huge reduction in initial growth was observed when planting occurred in the second half of the season. At the Venezuelan western llanos delaying planting more than one month after starting the rainy season causes poor survival and growth because the soil becomes water-saturated. In sites with bimodal rainy season special care must be taken with respect to this issue. Planting outside the appropriate season due to budgetary limitations and lack of planning are a common source of failure, mainly in State managed projects. Likewise, the opportune execution of weeding and pruning is very important including also the first thinning which should be made shortly after canopy closure. Below we discuss some of the most critical aspects of successful establishment and management of teak plantation.

5.1.2.1 Improved Plant Material for Establishing Successful Teak Plantations

For planting, teak vegetative material comes from seeds or vegetative propagation (clones). Careless selection of plant

Figure 1

Stages and main activities of intensively managed teak plantations. Critical activities are highlighted in red color.



Research centers devoted to teak genetic improvement — Table 1

Research center	Country	Website
Centro Cantonal de Hojancha	Costa Rica	http://www.cachforestal.com
CATIE		http://www.catie.ac.cr
GENFORES		http://www.tec.ac.cr/sitios/Docencia/forestal/Paginas/genfores.aspx
KFSC-KERALA Forest Research Center	India	http://www.forest.kerala.gov.in
YSG Biotech SND BHD	Malaysia	http://www.ysgbiotech.com

material is one of the main causes of plantation failure. There has been considerable progress in producing improved seed from seed areas and orchards, increasing the overall quality of plants used for many projects. To obtain considerable genetic gains in shorter time clonal propagation has shown to be an excellent option. Clonal seedlings from very exceptional trees are gaining acceptance (Goh & Monteuuis, 2015). Several institutions around the world (see Table 1) are producing clonal material of excellent quality in large amounts thanks to new propagation protocols (Goh & Monteuuis, 2012). Some results of growth and yield performance of clones as compared to traditional plantations are shown in Chapter 5.1.2.5. Besides gains in growth performance, stem and wood quality, some of these clones are pest resistant and can grow in soils traditionally considered unfavorable for teak.

5.1.2.2 Seedling Production Systems

Growing seedlings of the best quality is essential for the establishment of plantations with high potential for success. Plants and seedlings should be produced from certified seed from plus trees, seed areas, seed orchards or vegetative propagated seedlings from accredited sources. For producing plants at nurseries several production methods are used: stumps, plastic bags, rigid containers, and jiffies (see Figure 2). Shoot cuttings (stumps) from seedlings are used in many countries. They can be produced with simple infrastructure and transported to sites of difficult access. Its main disadvantage is that seedlings must stay in ground nurseries for more than six months (Rance *et al.*, 2014). In Brazil, disease problems have been reported with this material. Polyethylene plastic bags of various sizes were used in Venezuela. In bags, seedlings can be ready for planting within three months or less; however, vehicle transportation to the planting site is needed even for short distances. Rigid containers are designed specifically for tree seedling production. They come in various sizes, are reusable, occupy little space in nurseries and are easily transported, especially if plants are small-sized. Disposable small rigid containers are used to produce seedlings within time periods as short as six weeks. For containers, it is possible to prepare substrates of specific compositions, adding nutrients and mycorrhizae, and using hydro-gels to retain water after planting. The jiffies are small containers made from peat moss that have been successful in Central America. The Ellepot system is a container made of biodegradable paper produced in customized sizes with a special machine. Its advantage is that it allows more aerated and unconstrained root systems. However, it needs special plastic trays to keep the pots in place at the nursery. This method has been used for producing teak in Brazil. On the other hand, teak clonal vegetative material can be produced in clonal mini-gardens, which are capable of producing a large number of plantlets within a short period of time, in a very small space employing very high plant densities. In Brazil, the "clonal

Methods of teak plant production in nurseries: a) stump (adapted from Chandrasekhara-Pillai *et al.*, 2014), b) rigid container, c) ellepot system, d) clonal mini-garden. Photos b, c, d © Floresteca — Figure 2

a) b) c) d)

virtual mini-garden" can contain up to 40,000 plants/m^2 (Higashi *et al.*, 2000). Independently of the method, produced seedlings must be of good quality (good size and well-developed root system) prior to planting as a key to a successful plantation.

5.1.2.3 Site Selection for Planting Teak

Site selection is the most critical issue for successful E&M of teak. The concept of site includes the set of biotic and abiotic factors that influence tree growth. Teak is native to regions of South Asia with a monsoon climate. It develops on fertile soils of alluvial, limestone, and basalt origin (Kaosa-ard, 1989). Teak has been planted in a large variety of site conditions inside and outside of its native area across the tropics, including extremes of climate and soil conditions. Complex relationships between climate and soils (soil evolution depends on parent material and climate) and specific requirements of teak combine, so that optimal growth is limited to relatively small areas. E.g., in dry climates teak can be grown, but if soils have

Site requirements and limitations for teak plantations. Table 2

Site factor	Optimum	Limiting conditions	References
Cimatic/topographic			
Latitude	Tropics	Cold subtropical	(1)
Altitude	0-900 m	900-1300 m	(2)
Temperature	22-27	Freezing 2 colder months < 13°C Min (13-17°C) Max 39-43 °C	(1)
Precipitation	1200-2500	<750-1200, or >4000-5000 mm (4)(2)(3)	(2) (3)
Seasonality	3-5 months dry season	> 6 months / short summers, Minimum 3 months	(5)
Slope	0-25%	High windy slopes	(5)
Physiography	Bottom of valleys	Hilltop, dry windy slopes	(5)
Topography	Flat, undulated	abrupt, depressions susceptible of flooding, stoniness	(5)
Soil properties			
Soil origin	Alluvial, basaltic, Limestone, sandstone, quartz-ite, shale	Calcareous/lateritic	(2),(3)
Soil orders (only specific soil suborders are suitable)	Inceptisols, Entisols, Andisols, Alfisols	Vertisols, Oxisols, Ultisols	(6), (7), (8), (9), (10);
Soil horizons	Well-structured O, A, B horizons	Lack O/ A horizon, Bedrock outcrops, exposed acidid B horizon	(5)
Soil physical properties			
Texture	Loamy medium texture	Cohesive high clay, high sand, smectitic clays	(11)
Depth	Depth (90 cm- 2m)	Depth < 90 cm, hardpans, plintite, stoniness / chemical restrictions	(12), (5)
Water holding capacity	Good	Bad	(5)
Compaction	Non compacted	Very compacted	(5)
Bulk density	Low	High	(13)
Drainage	Good	Poor or excessive	(5)
Aeration	High	Poor	(3)
Soil chemical properties (see Chapter 5.1.4)			

Sources: (1) Pandey & Brown (2000); (2) Kaosa-ard (1989); (3) Balagopagan & Rugmini (2006) (4) Figueiredo & Sá (2015); (5) Alvarado (2013); (6) Jerez et al (2015); (7) Kollert & Cherubini (2012); (9) Alvarado (2012a); (10) Alvarado (2012b); (11) Krishnapillay et al. (2005); (12) Krishnapillay (2000); (13) Mahmud (2014).

poor water-holding capacity, prospects of a successful plantation are reduced. Moreover, teak requirements appear to vary according to genotype and site as reported in Central America, Brazil, and Africa (Alvarado, 2013; Matricardi, 1989; Drechsel & Zech, 1994). Careless assessment of site conditions can lead to plantation failure or poor growth. On the other hand, the feeling that it is possible to reach higher yields within shorter time periods highlights the need of precise assessment of site characteristics that favor (or limit) optimal growth with minimum risks. Table 2 presents the range of site factors in which teak growth can be acceptable to an optimum, as well as those factors that are limiting to teak growth including its survival.

5.1.2.4 Soil Preparation Practices

Several activities must be carried out to achieve a good soil preparation. Some operations are general for all sites, whereas others are specific to special site/genotype conditions. Adequate soil preparation must be realized to provide optimum physical soil conditions, improve water holding capacity, and enhance nutrient availability for optimum root growth. Soil preparation goes from minimum tillage systems to methods that imply the modification of some soil properties through mechanical, chemical, and biological procedures (see Figure 3). Soil tillage is often used to reduce soil compaction and improve superficial drainage. Tillage includes activities such as ploughing, disking, ripping, and subsoiling. The latter is used to break hard horizon layers and to improve the structure of clayed soils. Bedding consisting of making mounds improves drainage in soils that show minor excess water problems, such as small flooding during very short periods. In Venezuela, bedding is a common practice to avoid the effect of short flooding at initial plantation stages. Besides, it provides an increased volume of low bulk density, aerated soil. However, if during the growth season the soil water table is close to the surface, future growth will be poor. In México complex drainage systems have been built to avoid soil flooding produced by periodical river inundations. If soils are very acidic, liming and fertilization can serve as amendments (see Chapter 5.1.4).

5.1.2.5 Timber Productivity of Teak Plantations and its Relation to Site, Growth Characteristics, and Desired Products.

Teak has been planted, managed, and harvested in Asia for several centuries (Ladrach, 2009; Evans, 2009). Yet, the debate on teak timber productivity under management persists. Complications arise due to the introduction of teak on new sites around the world, differences and improvements in planting techniques, concerns with reduced productivity by soil degradation, and potential effects of climate change. For many years, the theory known as Liebig's "law of the minimum" predominated among foresters. According to this theory, the maximum growth of a forest is limited by the resource of the lowest supply in relation to tree requirements. However, new findings indicate that forest productivity can be limited not only by insufficiency of a single important resource; but also by simultaneous not linear interaction of low (or large) supplies of multiple resources (Binkley & Fisher, 2013).

Growth, Yield, and Productivity of Planted Teak Trees and Stands

Teak is considered a medium- to fast-growing tree that can reach large dimensions; although trees of more than 2 m in diameter and a height of 60 m have been reported, these are exceptional cases. On plantations from seed, dominant trees can reach on average 70 cm in diameter and 40 m height in 50-80 yr., but at age 40, the largest trees rarely surpass 35 m in height and 60 cm in diameter. In good sites and with appropriate establishment and management practices, at young stages height growth is fast (3 to 6 m/yr.), slowing after age 15. Diameter increment peaks at 3-5 cm when 3-6 yr.-old. Tree volume increases exponentially over several years, but maximum roundwood overbark volume of stems rarely exceed 2.5 m^3 per tree (50 cm dbh and 20 m of clear bole). At stand level,

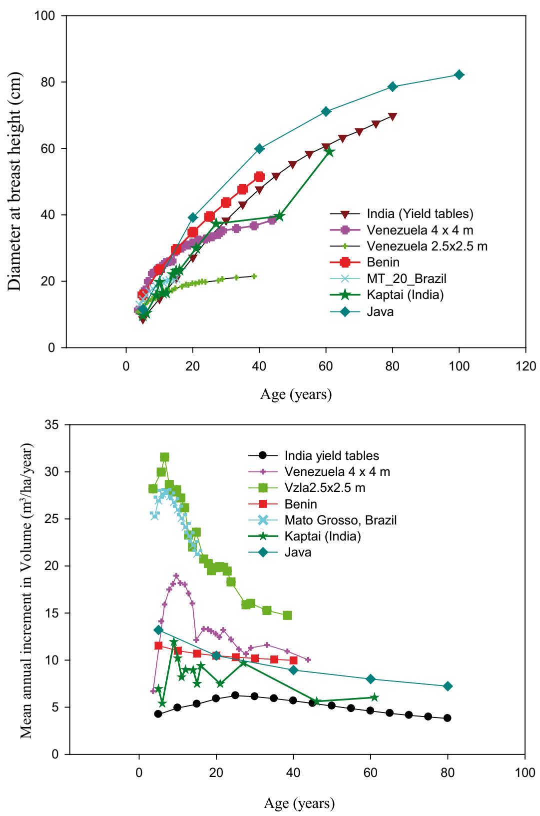
Figure 3

Soil preparation: a) ploughed soil for planting in Brazil (Photo: Floresteca); b) mounds formed by bedding in México; c) channels for draining excess water from teak plantations in Tabasco, México. Photos b,c © (M. Jerez)

a) b) c)

Figure 4

Teak productivity from measured data and yield tables in selected countries across the world (good site quality).



a) Average diameter at breast height; b) Mean annual increment in stand volume. Sources: Indian yield tables, India (Kadambi, 1972); Venezuela (Jerez, unpublished data); Benin, Africa (Houayé, 1993); Brazil (Drescher, 2004); Java (CEFAP, 1970)

size-density constraints impose limits to the maximum size and tree number that a site can support (e.g., stand basal area can reach a maximum of around 55 m^2/ha). Teak stand productivity is usually assessed by estimating total volume yield (m^3/ha) or mean annual increments in volume (i.e., total stand volume divided by plantation age [VMAI in m^3/ha/yr]). For teak, VMAI of 15-20 m^3/ha/yr are considered excellent; whereas, VMAI below 6 m^3/ha/yr is at the lower limit for profitable plantations (Kollert & Cherubini, 2012). However, in teak plantations VMAI should be interpreted with caution and be accompanied with additional information, at least of average tree dbh and age, as volume yields are affected by stand density. High VMAI can be associated with small average tree diameters, i.e., high volume increments per ha are easy to obtain in unthinned plantations (see Figure 4). In addition, volume estimation and prediction of roundwood standing volume (m^3) depends on measurement, sampling, and statistical issues. Caution is recommended in reaching conclusions in the absence of expert assessment. For example, traders use volume scales (Hoppus ton, Bereton system) for cut logs with specific dimensions and wood quality standards, and include volume discounts for wood quality, bark size, defect proportions, and stem form. Such product specifications are rarely considered when reporting yields of standing timber (Midgley *et al.*, 2015). Efforts must be made to develop volume and taper equations to assess the real commercial volume, taking into account bark/sapwood/heartwood proportions. At the same time, it is important to develop, standardize, and divulgate conversion factors to estimate and predict future commercial yield of specified products from standing volumes. In this sense, the development of globally uniform teak grading rules for timber from plantations must be discussed.

Larger figures of productivity are expected in clonal plantations than in seed plantations (see Figure 5). Results of clone growth around the world have been reviewed by Ugalde (2013). He reported VMAI of 32 m^3/ha/yr for clonal plantations from México and Brazil. In Mato Grosso, Brazil, 10-yr-old clonal plantations show annual diameter increments of over 3 cm/year. Moreover, these clones are showing exceptional height growth and large standing volumes because of greater stand homogeneity. Smit & Oestreich (2014) compared volume growth of clonal and seedling plantations of up to 9-yr-old and

Figure 5

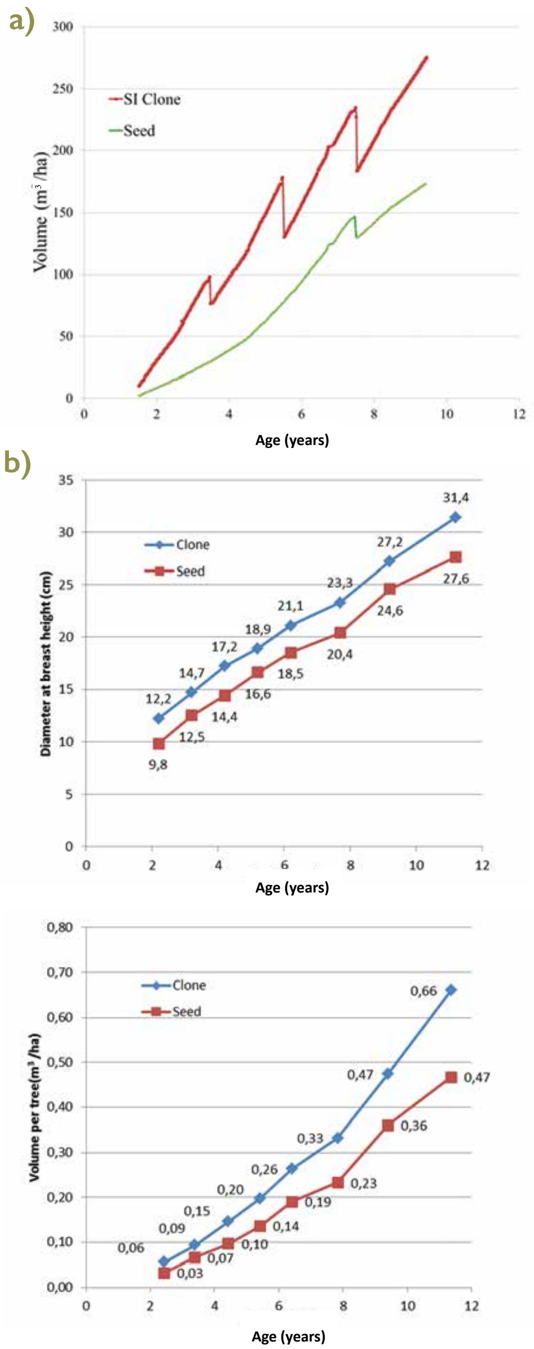
Clonal plantations in Mato Grosso, Brazil: a) plus tree for seedling production and cloning b) clonal plantation performance as compared to seedling plantation growing under similar site conditions; c) change in stem cross section with age of a clone tree (below) vs a seed tree (above).
Source: b) Floresteca, a, c) Smit & Oestreich (2014).

a) b) c)

Observed growth and yield of clonal vs. seed plantation in Brazil

Figure 6

a) Volume growth of a Solomon Island clone (SI Clone) vs seed plantation in Tangará da Serra, Mato Grosso, Brazil; b) observed diameter growth and c) volume per tree of clonal vs. seed plantations in Floresteca, MT, Brazil.



Sources: a) Smit & Oestreich (2014); b, c) Floresteca (2016).

from a managed clonal plantation of 17-yr-old in Tangará da Serra-Mato Grosso, Brazil (see Figure 6a). They found that clone plantation average diameter, volume per tree, and foliar area index were superior to those of seed by 64%, 146%, and 10%., respectively. Moreover, clone trees were more resistant to teak rust (*Olivea tectonae*) than normal seedling material, showed a tendency of self-pruning and a denser superficial root system. In 12-yr-old commercial plantations in Brazil (Floresteca, 2016) clones showed superior diameter growth (14%) and volume per tree (40%) than seed plantations on similar site conditions (Figure 6b, c). Results from teak clonal plantations are very promising; however, a global monitoring plan is required to assess clonal performance under operational conditions from a biological and financial standpoint, and to determine under which conditions clonal plantations should be preferred over traditionally improved seed plantations.

Site Index

Site index (SI) is used to subdivide taxonomic units into areas of similar productivity or "site qualities", and they are based on the total height reached by dominant trees in a plantation at a given base age. Thus, a larger height at base age implies better site quality and greater productivity. One advantage of this approach is that dominant height is independent of stand density (within the range used in forest plantations). SI curves were developed for teak plantations in many countries and regions, serving as a useful tool for comparing teak productivity across the world. However, this method should be improved to accommodate the effects of climate change (e.g., precipitation variability), improved management techniques, and clonal material. Combined approaches of SI, climate, physiography, and soils analysed with advanced multivariate and geospatial techniques are needed to predict future teak productivity. In Venezuela, SI for teak can be predicted for alluvial soils from a flow chart including soil variables: pH, texture, and drainage (see Figure 7).

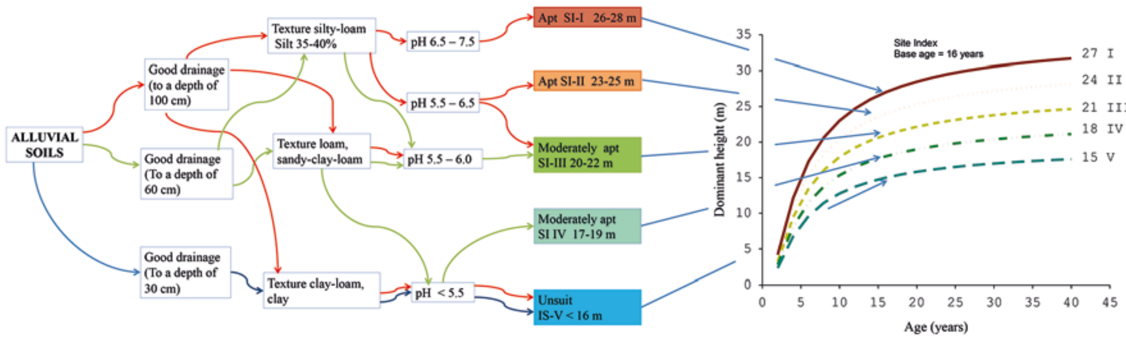
Recent advances in soil studies and determination of teak nutrient requirements for increasing plantation productivity and further sustainable management have been made in several countries. For example, Matricardi (1989) determined the relative importance of various soil factors in relation to teak productivity in Brazil (see Table 3).

5.1.3 Standing Stock Management

Standing stock management in even-aged forest plantations refers to the regulation of the size and number of trees from implantation until final harvest. Two phases are important in this stand management (see Figure 1): a) establishment phase, from implantation (initial spacing) to canopy closure when a desired homogeneous quality tree stocking is reached. In this stage trees are responsive to fertilizers and weed control. Weed control is critical because teak is very sensitive to weed competition; and b) management phase: from canopy closure to final harvest. In this phase thinning prescription (none to several thinning operations) are carried out to reduce inter-tree competition and concentrate site resources in the best trees. Age, frequency, intensity, and removed tree classes must be considered. Unpredictable events or competition (self-thinning) can reduce standing stock. Optimum stocking

Flow chart based on soil properties (drainage depth, soil texture, and pH) for predicting likely site index for teak plantations in alluvial soils of the western Llanos of Venezuela. Figure 7

The chart is useful to predict site index in candidate areas for planting by identifying through soil analysis, the specific combinations of properties in the order indicated in the chart.



regimes must consider biological and financial aspects to meet clear goals in terms of timber volume and quality at final harvest. This can be a difficult task given the large amount of possible alternatives, making experimental and observational studies insufficient. Information from the experience, observational data (permanent and sample plots), ecological and biological principles, as well as economic aspects, have been integrated and translated into quantitative models, to show the effects of initial spacing and thinning alternatives on growth and yield through the rotation. Models can go from improvements of existing yield tables and size-density relationships indices to sophisticated growth and yield models including empirical and eco-physiological ones. They can produce some important insights not apparent from field studies.

5.1.3.1 Initial Spacing and Thinning Prescriptions, Pruning

The initial stand density should be planned to produce homogeneous stands with large trees for the final harvest. Traditional spacing in teak is squared (e.g., 3.0x3.0m); however, a careful selection of initial spacing is valuable. With improved vegetative material and E&M techniques, initial densities were reduced from 3000 trees/ha (1.8x1.8 m) to near 1800-1111 trees/ha (2.35x2.35-3.0x3.0 m) in the last 40 years. Lately, wider spacing 3.5x3.5 or 4.0x4.0 m and even 5.0x4.0 m (816-625-500 trees/ha) are recommended in Central America (Malmström, 2013) and Brazil. Yet, many growers continue using high densities (1111 to 1667 trees/ha). Tree spatial arrangements should consider effects on tree growth and easing of future tending and management operations. Narrow spacing is appropriate if producers cannot ensure good quality seedlings, or site preparation practices. The expectation is compensating for tree mortality, bad form/poor growth trees, and reducing the need of weeding due to faster canopy closure. Nevertheless, narrow spacing will require an early intense first thinning, to avoid reduction in diameter increment due to inter-tree competition. Wider spacing is recommended for producing large dimension logs in shorter time and for reducing costs in plants and site preparation. However, weed control and early pruning will be necessary. With no improved seedlings, problems such as buttressing, and early forking are common. In Venezuela, spacing trials showed that wide spacing (4.0x4.0 m) produced larger diameter trees than narrow spacing, but these had larger branches and more taper due to buttressing (Vincent *et al.*, 2000). In Tanzania (Zahabu *et al.*, 2015) reported 4.0x4.0 m spacing produced up to 50% more heartwood, 30 yr-old than 3.0x3.0 m spacing. Mixed results between wide and narrow spacing have been found in relation to wood properties. E.g., Sibomana *et al.* (1997) found lower basic density, but no differences in mechanical properties. In Brazil, (Lima *et al.*, 2009) a significant influence of spacing only on apparent wood density is reported.

In dense teak plantations, the first thinning should be made as early as possible (between age 3 and 8) depending on site quality, initial spacing/survival, and expectations of any commercial products (e.g., biomass, poles). In Latin America, where short rotations are desired (16-25 yrs), a first non-commercial early thinning is recommended at ages 3-6. In dense stands, after canopy closure, tree crown length and lateral expansion are rapidly reduced, leading to a notorious reduction in diameter increments if thinning is delayed for too long (Morataya *et al.*, 1999). Ladrach (2009) recommends early thinning operations on the basis of practical and financial considerations, remarking that profits from final harvest are the largest proportion with respect to profits from thinning operations, because of low value products and larger operational costs per m^3 of thinning. Moreover, thinning operations

Table 3

Soil characteristics associated with teak productivity in Brazil. Numbers 1 to 9 indicate the ranking of relative importance of each factor.

Soil factor / element*	Unit	Soil categories and related growth performance (m^3/ha/yr)			
		Optimum (15-20)	Good (10-14.99)	Marginal (5-9.99)	Unsuitable (< 4.99)
(1) Ca	mEq/100g	>4.0	1.5-3.9	0.5-1.59	<0.49
(2) Al	mEq/100g	0.0	0.0-0.2	0.21-1.0	>1.0
(3) OM	%	>4.0	2.5-3.99	0.8-2.49	<0.80
(4) Ca + Mg	mEq/100g	>6.0	2.5-5.99	0.8-2.49	<0.8
(5) Clay	%	35-45	15-35 and 45-55	5-15 and 55-65	<5 and >65
(6) K	ppm	>120	40-120	15-40	<15
(7) P	ppm	5-10	3-5	1-2.99	<0.99
(8) Mg	mEq/100g	2.0-4.0	1.0-1.99	0.3-0.99	<0.3 and 4.0
(9) Soil depth	cm	>120	60-119	30-59	<30
S	mEq/100g	>8	4-8	2-4	<2
CTC	mEq/100g	>10	4-10	2-4	>2
Sand	%	55-65	65-85 and 45-55	85-95 and 45-35	<35 and >95
pH (H_2O)	UM pH	6.2-7.2	5.5-6.1	4.5-5.4	<4.5

**Ca (Calcium), Al (Aluminum), OM (organic matter), Mg (Magnesium), K (Potassium), P (Phosphorus), S (Sulphur), CTC (Total Cation exchange Capacity), pH.*
*** mEq/100g = miliequivalents per 100 grams of soil, ppm = parts per million.*
Source: Adapted from Matricardi, 1989)

can damage residual trees, reducing their growth or killing them (see Figure 8). Criteria other than age are used to prescribe thinning operations, average height, which accounts for the effect of site quality on stocking. E.g., in Costa Rica first thinning is recommended when trees reach 8.0 m height, at 3-6-yr-old (Chaves *et al.*, 2016); and 9-9.5m in Malaysia (Krishnapillay, 2000).

Simple indices such as stand basal area (SBA) are used empirically in teak plantations to prescribe thinning schedules, assuming limits of optimal stand occupancy. For example, keeping SBA= 15-20 m^2/ha has been considered a standard for maintaining maximum SBA increment, and therefore volume increment. However, optimum SBA limits vary depending on site quality and production objectives; thus, SBA bounds favoring maximum diameter increment differ from those favoring maximum SBA increment. Jerez *et al.* (2015) adapted a simulation whole-stand model based on this principle for simulating the effects on growth, yield, and carbon sequestration of site quality, initial spacing, stand mortality, and rotation age in multiple

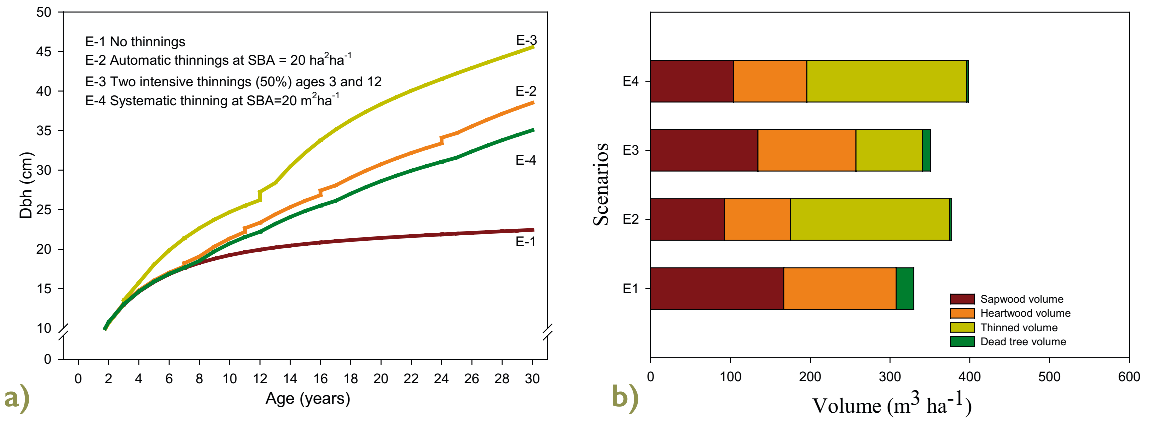
Figure 8

Thinning in teak plantations: a) mechanized thinning (Brazil), b) nine yr-old plantation after third thinning (Venezuela), c) fourth thinning in a 35-yr-old plantation (Venezuela). Photo a) © Floresteca (2016); Photos b) & c) © M. Jerez.

a) b) c)

Simulated outputs for a) diameter growth (dbh) and b) total volume yield (sapwood, heartwood, thinned and dead trees) in four stocking management prescriptions (Scenarios E1-E4) from Jerez *et al.* (2015) model.

Figure 9



scenarios. For scenarios considering 30-yr rotation, unthinned stands produced the largest total volumes at final harvest, but low average dbh (Figure 9a). Scenarios with intense early thinning (3- and 12-yr.-old) and wide spacing (3.5x3.5 m) showed the largest average diameter, but lower final yield volume, however, utilizable volume was larger than in unthinned stands. Light, frequent thinning tended to produce lower final volume, but larger utilisable volume than any other scenario; however, final tree size was lower. It also should be noted that more total heartwood is produced in unthinned plantations, but this is distributed in a large number of small trees; whereas the early thinning scenario concentrates on a larger proportion of heartwood in fewer trees (Figure 9b).

Light, spaced thinning operations can be advantageous if a good market for intermediate products exists or when there is no price differentiation for quality logs (e.g., Venezuela). Jayaraman & Rugmini (2008) used a growth and yield model, as well as data from Indian teak yield tables to determine thinning regimes that maximized net present value; and found optimal density that maximize benefits under Indian economic conditions, with a good market for poles and interest rates of around 2-3%. Pérez & Kanninen (2005) compared three competition indices used to prescribe thinning operations and proposed several stand growth scenarios for teak management in Costa Rica. They suggested that a crown competition index was better than traditional SBA and Reineke stand density indices, as the former matched well the observed growth of teak; whereas the others generated conservative thinning prescriptions with narrow limits which favor too frequent thinning interventions. They proposed four and five thinning operations beginning at age 4 for rotation lengths of 20 and 30 years in good site quality. Quintero & Jerez (2013) with data from permanent and inventory plots measured over more than 30 years developed a model combining simulation and heuristic optimization techniques to obtain optimal thinning schedules under various stand and financial conditions. They found that depending on site quality and initial spacing, the optimal prescriptions in terms of maximising the net present value are three 30-40% intensity thinning operations beginning at age 5. Higher interest rates tended to favor earlier, more intensive thinning operations in concordance with current trends by private companies.

Pruning

Pruning is essential for obtaining high quality timber for the international market, as it improves stem quality by increasing the proportion of free knot timber. However, pruning is an expensive activity and it can affect tree growth if

Pruning. a) Mechanized pruning in Brazil; b) High pruning in 9-yr-old teak tree.
Photo a) © Floresteca (2016), Photo b) © M. Jerez

Figure 10


a)
b)

an excessive proportion of live crown is removed: Hence, pruning must be carefully planned and executed. The dry season is the best time for pruning, and it must be carried out progressively to ensure a good ratio of live crown/total height. In teak, the first pruning is done at an early age and up to 3-4 m height; then a second pruning is done up to 6 m after the first thinning. For good/medium site quality in Costa Rica, Pérez & Kanninen (2003) recommend a first pruning of 2-3 m when stand height is 4-5 m, a second one at 4-5 m when height is 9-10 m and up to 7 m when height is around 12 m. Ugalde (2013) recommends that pruning height should be increased at intervals determined by the desired log length; thus, for getting at least four logs (2.3 m length), clear commercial boles should be at least 10 m. Experiments are being carried out in Brazil to study the biological and financial effects of pruning above six meters (Figure 10). Apart from producing more free-knot wood, it has been observed that adequately pruned trees show more cylindrical boles, better stem shape, and less twisted wood. Possible disadvantages include lower growth of pruned trees and loss of free knot timber when logs are squared. Also, pruning can affect tree health, as it might facilitate the development of tree diseases such as fungus, depending on how and when it is executed.

5.1.3.2 Rotation Age

For solid teak timber production, optimum harvest age depends not only on stand volume, but on large volume of individual trees (boles of large diameter, length, and defect free) and wood quality. Considerations on wood quality include knot size and frequency, wood defects, and wood physical-mechanical properties such as strength, durability, and stability. Also, attractiveness (wood color, grain, etc.) is very important. Again, financial considerations are critical, given the need of fast returns, although environmental concerns and perception issues can influence decisions on this matter. Rotation lengths of teak plantations decreased from 120 years to lengths as short as 16 years, which is considered the minimum to obtain a final yield with sufficient wood of acceptable quality to cope with preferred international market standards. In India and Indonesia, state-owned companies use 60-80 year rotations for producing high quality wood for veneer. On the other hand, in Latin America, very short rotations (20 yrs) are preferred by private companies and smallholders that need rapid returns (Jha, 2016).

High interest rates have a large influence on shortening rotation ages at stand level (Malmström, 2013). Through models, Jayaraman & Rugmini (2008) found that raising interest rates from 2 to 5% decreased optimum (maximum net present value) rotation age from 60 to 40 years. In a context of private investments, rates for forestry projects vary from 6-15%; thus rotations above 25 years have low economic feasibility, despite government support or subsidies for E&M. On the other hand, the existence of a log price differentiation that account for diameter, length, heartwood proportions, amount and types of defects, has an important influence on rotation length. In Venezuela, where no price differentiation between young and old age teak exists, stands have been harvested at age 6 and then managed as coppice. Nevertheless, most commercial teak plantations are being managed to sell timber in the international market, which poses a minimum set of specifications to meet. In this sense, an objection against short rotation in teak plantation is that although relatively large log sizes can be obtained, wood quality from fast growth plantations is inferior to that of old-growth timber. However, several studies on fast-grown plantations of various ages did not show significant differences in certain physicomechanical properties such as basic density, modulus of rupture, of elasticity, and maximum crushing stress suggesting that teak 13-21-yr-old is not inferior to trees 55-65-yr-old (Bhat, 1998). Likewise, studies on 14- and 22-yr-old teak in Brazil showed decay resistance comparable to that of naturally grown teak (Laming & Van der Zee, 2008). Polato *et al.* (2003) observed that short-rotation teak wood is not significantly inferior in density and strength compared with teak from natural forests, although it is less durable due to a lower proportion of heartwood and extractives content. Moreover, fast

Changes in heartwood proportions with age in teak plantations. a) four-yr-old teak (Venezuela), 35-yr old teak (Venezuela), c) 50yr-old teak logs (Ecuador). Figure 11
Photos © M. Jerez.

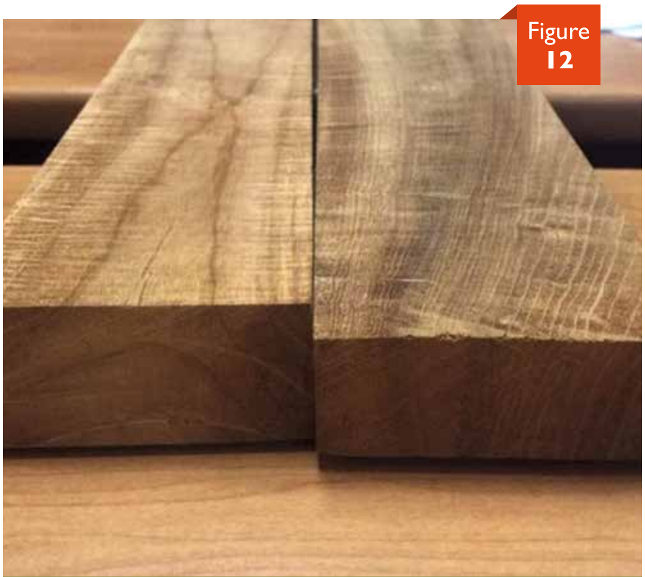
a) b) c)

grown teak has higher heartwood percentages as compared with slower grown teak of similar age (Pérez & Kanninen, 2005; Midgley *et al.*, 2015).

In support of old-growth teak timber being of superior quality, Matumura & Kawasaki (2012) pointed out that teak harvested in long (50 yrs) rotations produce logs of higher decorative value and more stable shrinkage and high and stable bending strength at the upper part of the stem compared to short rotation teak (14-16-yr-old). Also, at the outer part of the stem there is a smaller variation in wood density. Moreover, the proportion of heartwood would reach up to 90 percent against 77 percent in 51-52-yr-old trees, and only 30 percent in 8-yr old trees (Figure 11).

Perception by consumers of high price teakwood is a barrier to accept timber from short rotation ages because it is considered of inferior quality than natural forest timber (Thulasidas *et al.*, 2008). According to Bhat & Ma (2004), native teak tends to produce darker, denser and a greater proportion of heartwood and it is thought to be stronger by consumers and artisans than fast grown teak (However, see Figure 12). Nevertheless, in the future, teak from plantation will continue increasing its share of the global market. Use of fast growing clones that also produce greater quality and decorative timber will be able to reach larger prices in the market. Also, perception of what is quality teak can be different from that of traditional markets.

Figure 12



Sawn timber from Brazil (left, 20-yr-old) and Indonesia (right, 50-yrold). Note the similarity in color. Photo © Floresteca (2016)

On the environmental side, teak plantations can be promoted as a carbon sink. Higher prices in the C market would favor later thinning operations and larger rotation ages (Malmström 2013; Quintero & Jerez, 2016).

Large private projects or state managed projects operating with low interest rates could think about keeping some areas to manage in long rotations to produce very high quality wood and addressing in part issues on carbon sequestration. Combining alternate land uses (i.e., environmental services) or tree species (e.g., nitrogen fixing trees) in a same stand are attractive options (Jha, 2016). However, for private investors expecting high interest rates this is not a feasible option for now.

Finally, management plans of standing stock can be altered by larger scale or unpredictable events (e.g., climate events, price volatility, and opportunity costs) that could shorten or lengthen the planned final harvest. For example, climate events such as "El Niño" are suspected to affect teak growth in Latin America. Malmström (2013) observed that owners in Central America make final cuts much earlier than recommended. At project level, the rotation of particular stands can be shorter or larger than the optimum for single stands due to opportunity costs (e.g., very favorable market prices) or to meet annual harvest quotas (Quintero & Jerez, 2016).

5.1.4 Nutrient Management

Although teak grows well in many sites with adequate climate conditions and diverse soil categories; the chemical properties (i.e. nutrient availability, soil pH, exchange cation capacity) of many soils can be favorable or limiting for teak growth (Table 4). Usually, in suitable sites, nutrient supply by the soil and inputs from atmospheric, biological, and weathering processes allows good development of teak plantations; however, maximizing biological teak growth and financial returns require site-genotype specific fertilizer plans (rate, method, and time) based on field experimentation (Gonçalves *et al.* 2014) .

Traditional fertilisation practices and trials for teak in Latin America were reviewed by Alvarado (2012b) and in Asia-Africa by Kumar (2011) showing mixed results. Sometimes fertilizer produced fast height growth rates increasing the risks of tree buckling in windy sites. Other experiments showed no response. These differences might be attributed to the synergies among site factors influencing nutritional demand and availability. On teak, positive responses are more likely in low fertility stands; in contrast, fertilizing stands where natural fertility meets the tree's requirements could be unresponsive. In addition, weed competition and susceptibility to herbivore can reduce responses (Kumar, 2005). In general, chemical fertilization on low quality sites can increase the volume by 30-50 %. Although fertilization is done usually only in the establishment phase fertilisation together with thinning operations is increasingly practiced.

Lately, an approach known as nutrient management has been adopted. This method looks for satisfying nutrient requirements of planted trees to increase their productivity in terms of wood, at the same time of minimising nutrient losses and maintaining soil productivity (Fernández-Moya, *et al.*, 2014). Several researchers have attempted to establish nutrient requirements and their dynamics with age for teak plantations under various site conditions (e.g., Drechsel & Zech, 1994, Fernández-Moya *et al.*, 2014). This is a difficult task due to the complex dynamic interrelationships among soil nutrients. Therefore, methods for acquisition and interpretation

Reference ranges of soil chemical properties to consider in teak plantations. Values shown depend on the particularities of each study such as soil depth, plantation age and analysis technique. Table 4

Chemical properties	Optimum	Limiting conditions	References
Acidity (pH)	5.5-8.0	< 5.5 or > 8.5	(1)
N content	0.03-0.12%	-	(2)
P	5 mg/l or 150-160 ppm	-	(1)
Exchangeable K	0.14-0.36 meq/100 g soil	-	(2)
Ca	high (10 cmol+/lt)	-	(3),(4)
Mg	>10 cmol+/lt	-	(5)
Relative macronutrient requirements	Ca>N>K>P>Mg>S (CR) N>P>K>Ca>Mg>S (Africa)	-	(6),(1)
Relative micronutrients requirements	Fe>Zn>B>Mn>Cu	-	(6))
Cation exchange capacity	10 meq/100 g CA+Mg+K	< 5	(1)
Mn	-	<15 ppm	(1)
S	>8 mEq/100g	<8	(8)
Al saturation	3%	>5%	(7)
Ca saturation	>67%	-	(7)
K saturation	3.09%	<3	(4)
Organic Matter (%)	>4 %	<0.8%	(8)

Sources: (1) Drechsel & Zech(1994); (2) Mahmud (2014); (3) Balagopagan &Rugmini (2006); (4) Fernández-Moya et al. (2015); (5) Mollinedo (2003); (6) Alvarado (2013); (7) Alvarado & Fallas (2004); (8) Matricardi (1989)

** N (Nitrogen), P (Phosphorus), K (Potassium), Mg (Magnesium), Al (Aluminum), Ca (Calcium), OM (organic matter), S (Sulphur),*

*** mEq/100g = miliequivalents per 100 grams of soil, ppm = parts per million, cmol+/lt = centimol/liter.*

of data on nutrient soil availability and requirements of trees have been developed. Examples are: Diagnosis and Recommendation Integrated System (Drechsel & Zech, 1994), dynamic nutrient balances (Alvarado, 2012a), and multivariate analysis (Fernández-Moya *et al.*, 2015).

The soil reaction (pH) affects nutrient uptake and availability in teak plantations. In low pH (< 5.5) soils, teak grows poorly. There are complex relationships of base saturation, CIC, Ca saturation and exchangeable Al acid saturation. In the tropics low pH is associated with high exchangeable Al interfering with the absorption of N, Ca, Mg, S, Mb, Cu, and B. In Costa Rica, Alvarado & Fallas, (2004) and Panamá Mollinedo *et al.*, (2005) suggest that in acid soils (pH< 6), Al saturation should be < 4% and Ca saturation ≈ 68% for optimal teak growth. A widespread amend consists in liming (incorporating lime and gypsum to the soil) accompanied by fertilising with P and micro-elements (Alvarado, 2013). Also, vesicle-arbuscular mycorrhizae (VAM) increase teak trees tolerance to acidity or high Al concentrations (Alvarado *et al.*, 2004).

The impacts of high nutrient demands of teak plantations on soil reserves have been scarcely studied (Kumar, 2005). Usually, tropical soils are poor on nutrient reserves and are exposed to erosion, nutrient and organic matter losses under anthropic intervention. Causes of nutrient decline are timber extraction, poor site preparation (e.g., burning and scarification), leaching before crown closure, and nutrient immobilisation in the litter layer in mature plantations (Fernández-Moya *et al.*, 2014). According to Jha (2016) harvesting is the main cause of nutrient outputs from teak stands and determined that this operation could cause unavoidable losses by bole wood extraction and avoidable losses (fuelwood, leaves, and roots removal) suggesting that nutrient losses in teak monocultures could be one cause of teak productivity decline. Kumar (2005) in India, Fernández-Moya *et al.* (2014) in Panamá and Costa Rica; and Nwoboshi (1984) in Nigeria reached similar conclusions. Overall, results showed decreasing N concentrations with age in all tissues, and mixed changes in K and Mg (Fernández-Moya *et al.*, 2013). Depending on the element, 23 to 73% of the nutrients accumulated in mature stands can be removed in the final harvest (Fernández-Moya *et al.*, 2014).

5.1.5 Hazards

5.1.5.1 Pests and Diseases

A large number of pests and diseases affect teak plantations, most of them originate in the teak natural habitat.

With the introduction of teak to new regions, some pests have spread worldwide. Argüedas, (2013) reviewed main pests and diseases on teak planted in Latin America. Also, Ugalde (2013) reviewed this topic on a worldwide basis.

The insect pests of teak can be broadly classified as defoliators, stem borers and root feeders. The defoliator *Hyblaea puera* (lepidoptera) is the most widespread and serious pest being present across the tropical regions. Until 1995 outbreaks occurred only in native regions of Asia. In Latin America, this pest was first reported in Costa Rica (1995), in Brazil (1996), and in México where in 2010 more than 5000 ha were affected until 2013 (Cibrián-Llanderal *et al.*, 2015). In the past, this pest was almost ignored; but today serious concerns have arisen among commercial companies growing teak in 20-30 yr rotations. Effective biological control was reported in *Bacillus thuringiensis* (Sudheendrakumar, 1997). Chemical pesticides (Spinetoram) were used in México (Cibrián-Llanderal *et al.*, 2015). The economic impact of this pest was only assessed for *H. puera* in Kerala, India.

Control of defoliators is easier as they are quickly detected. However, infestation by borers like *Alcterogystia cadambae* is visible only after advanced infestation, causing severe impact. Only prevention and silvicultural treatments can help to reduce infestation. On the other hand, leaf-cutting ants are becoming a common problem in Latin America. Filho *et al.* (2006) in Brazil reported damage to teak by the leaf-cutting ant *Atta sexdens rubropilosa*. The attack occurs at any growth stage, but is more damaging in young plantations as it defoliates the crown and kills the apical bud, causing forking and delayed growth (Figure 13a). In the Northern Territory of Australia the giant termite (*Mastotermes darwinensis*) has been a limiting factor in the development of teak plantations (Robertson & Reilly, 2004). In Mato Grosso, Brazil, (Borges *et al.*, 2015) observed canker lesions producing heartwood rot and dieback of teak. Incidence ranged from 5-10% of trees across all inspected commercial fields. De Pieri *et al.* (2011) described the propagation throughout the Americas of *Olivea neotectonae*, the causal agent of rust teak (Figure 13b). In addition, phanerogamic parasites (mistletoes, Loranthaceae) are infecting plantations of more than 7-yr-old stands around the world.

Integrated pest control management must be adopted to prevent and minimise damages. Practices include chemical, biological, cultural, and silvicultural measures. From a global perspective, pest and disease management issues in teak plantations have to be taken seriously by growers to avoid losses in productivity. Research for quantifying potential economic damage is necessary in the global context. Also, genetic improvement for obtaining pest resistant plants is necessary. Some clones in Brazil have shown resistance to teak rust and Cankers (Borges *et al.*, 2015).

5.1.5.2 Fire and Other Hazards.

Teak is a species which is resistant to fire as long as they are not intense or repeated frequently on the same stand. Young trees can suffer serious and permanent damage because their bark is not thick enough. Also, fire stimulates growth of lateral shoots in the lower part of the bole, spots in the wood, and facilitates the penetration of pathogens through the wounds at the stem base. In Venezuela, basal stem holes can reach more than 1.5 m in height (outside or inside the tree). This occurs in thinned plantations where large branches have been left as residuals. Moreover, fire can cause nutrient losses due to burning of organic matter and litter. An

Figure 13

Hazards in teak plantations: a) Attack of leaf cutting ants (Venezuela); b) Tree seedling attacked by teak rust (Olivae tectonae) besides rust resistant clone tree: (see color leaf area) Source: Floresteca; c) Effect of wind on a 2-yr-old teak plantation (Venezuela)

Photos a and c © M. Jerez; Photo b © Floresteca (2016)

a) b) c)

organised prevention and fire patrol team with the necessary equipment and infrastructure (observation towers; communication devices) should be part of the staff in large projects.

Site selection is the best way of avoiding problems with strong winds that could damage the whole plantation. However, on many sites, strong winds can eventually occur and topple or bend very young trees that have grown very fast in height, especially if they have been fertilised (Figure 13c). Also, after intensive thinning in mature plantations, many trees can be felled by winds, especially on high slope sites or on soils with weak root penetration ability.

5.1.6 Concluding Remarks

The following issues are critical for the success of teak plantations to produce solid timber quality:

- good site selection, use of genetically improved plant material, and adequate soil preparation are of utmost importance;
- careful planning of standing stock management, including initial spacing, thinning prescriptions, and harvest age based on biological and financial considerations to obtain the desired products in the shortest time possible;
- timely execution of several operations. For example, consideration of planting time, pruning, and thinning operations;
- an early first thinning (3-to 8-year-old) depending on the desired products, site quality, and genetic material. This is necessary even if there is no market for the products, as it is essential to avoid an early decrease in tree diameter to obtain the largest stem size within the shortest possible time. Growers should not be afraid of doing intense thinning, especially at early stages. The investment made in cutting trees with little or no value will be largely compensated by the value obtained at the final crop.
- pruning to get knot-free high quality timber for the international markets.
- assessment of nutrient needs of teak along the rotation. Standardise protocols to evaluate fertilisation responses and scale them to operational level;
- management of pest and diseases has to be taken seriously by growers to avoid losses in productivity. Further work on quantifying potential economic damage and on genetic improvement will be necessary to obtain pest resistant plants;
- it is of utmost importance to have a good monitoring plan which helps not only to know the dynamics of growth and yield but to follow the correct and timely application of silvicultural operations to meet the desired management goals. The establishment of permanent plot networks and measuring additional variables is needed to get more precise information in order to be able to predict growth and yield, and especially on quality issues such as stem form and defects that may affect merchantable volumes.

The following trends are observed:

- Timber from fast growing plantation appears to have physical/mechanical properties as good as of those of timber from old-growth plantations. However, perception and decorative issues can be a barrier to penetrate the market of natural forests teak. Thus, although it is unlikely that teak from fast-grown, short rotation plantations reach the average prices of old-growth teak, its market will continue to expand in the near future;
- private companies and small producers in Latin America favor the use of wider spacing, earlier and more intense thinning, and shorter rotation ages (15-20 years), owed to the prevailing high interest rates for plantation projects, as well as the need of income from the final harvest as early as possible. Improved material and adequate silvicultural practices are mandatory for such purposes;
- sustainability and environmental services (e.g., carbon sequestration) are an increasing concern in forest plantation management. The use of the best silvicultural practices in every stage to reach sustainability goals can help to guarantee sustainability;
- adoption of modern concepts and techniques of intensive and sustainable forest management (e.g., precision forestry, nutrient dynamics, and informatics including advanced remote sensing techniques, optimization, and simulation models).

The following are tentative policies that global and national institutions could adopt or reinforce:

- Develop mechanisms to make planting teak an activity that is attractive both for tree growers and for investors;
- promote the exchange of information on the establishment and management of teak plantations around the world;
- develop globally uniform grading teak rules for timber from plantations. Standardise and divulgate conversion factors to estimate and predict future commercial yield of specific products from standing volume estimations.
- favor initiatives and search for funding to propose and execute international projects for studying the performance of improved genetic material under a wide set of site conditions;
- stimulate the incorporation of teak plantations under sustainable management schemes;
- analyse impacts of certification issues in enhancing sustainability of teak forest plantations;
- work to reduce negative perception by people in relation to teak plantations;
- inform and facilitate the access to improved genetic material, especially for small holders;
- evaluate the impact of regulations in the process of establishment, management, and commercialisation of teak plantations;
- devise policies to allow the growers obtain added value for their products or further benefits in the value chain;
- develop mechanisms of participation and benefits from teak plantations of stakeholders such as communities and workers;
- favour the creation or reinforcement of institutions for providing small producers with technical support for establishment and management of teak plantations.

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5.2 The Significance of Planted Teak for Smallholder Farmers

James M. Roshetko and Aulia Perdana[17]

5.2.1 Introduction

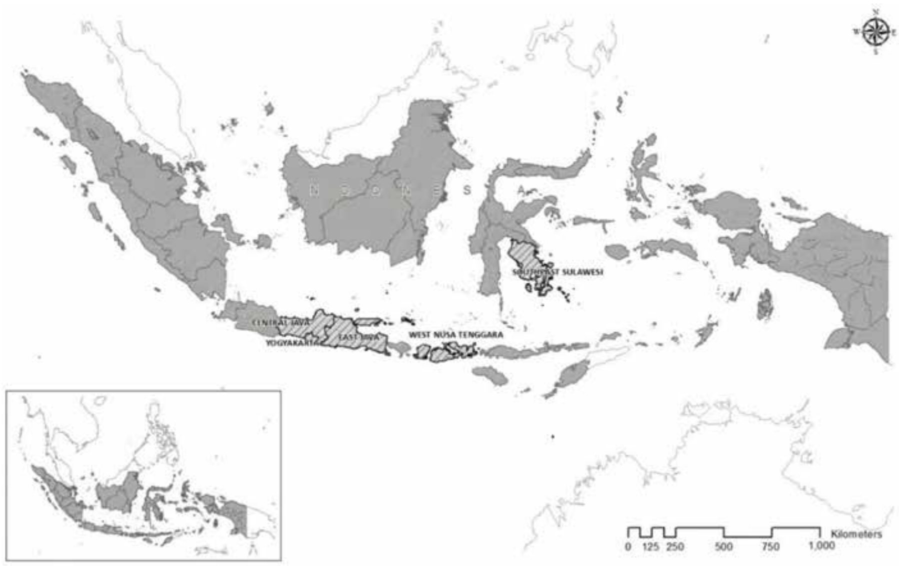
Teak (*Tectona grandis*) is most widely known as an industrial plantation species. There is a minimum of 4.3 million hectare of teak plantations across the world; 83% are found in Asia, primarily in India, Indonesia, and Myanmar. Smallholder farmer plantings are currently a minor component of the global teak estate, comprising 19% of the area in Africa and Asia, 31% in Central America, and 34% in South America (Kollert and Cherubini, 2012). With market demand exceeding the sustainable yield of large-scale plantations and natural forests, smallholder production holds potential as an important source of teak for industry. The second largest producer of teak behind India, Indonesia, has a very well developed smallholder teak farming sector, which is concentrated in Central Java, where farmers have been growing teak for over fifty years (Roshetko *et al.*, 2013). On Java there are approximately 1.5 million farmers cultivating 444,000 ha of tree-based agroforestry systems, where teak is the dominant tree crop; an additional 800,000 ha of smallholder agroforestry systems, in which teak is a component, occur in other parts of the country (Nawir *et al*., 2007; Figure 1). Smallholder-produced logs (diameters less than 30 cm) account for up to 80% of the teak used by small to medium industrial producers (Achdiawan and Puntodewo, 2011), which represent over 90% of the Indonesia's main teak furniture industry in Jepara (Yovi *et al.*, 2013). Indonesia is a compelling case regarding the significance of smallholder farmers to the teak industry, as well as of teak cultivation to smallholder farm families.

This chapter summarizes common and best practices regarding the sustainable and productive management of smallholder teak systems. It focuses on the example from Indonesia and encompasses relevant information from other countries. Recommendations and guidance are provided.

5.2.2 Socioeconomics and Culture

Teak is grown by smallholders in mixed farming systems in many tropical countries. These systems enable farmers to diversify production, reduce farm risk, contribute to food security, and generate much needed income. In Indonesia, Javanese farmers started growing teak in the 1960s. Average family landholdings are about 1 ha, varying from 0.5 to 3.0 ha, and consist of multiple parcels. Rohadi *et al.* (2011) report, that on 10% of farmland teak woodlots have been established, with other parcels containing teak in mixed systems. For families in central Java, teak is a valuable asset and a cultural icon. Half of farmers plant teak for family savings; a quarter planted teak primarily as cultural heritage; only 15% of farmers planted teak to maximize income. The management of teak systems is a shared responsibility between men and women. Women are primarily responsible for the management of agricultural companion crops and fuelwood collection, while men are responsible for timber tree management and sales (Roshetko *et al.,* 2013). Teak agroforestry systems provide 40% of household income – 25% from agricultural production, 12% from teak, and 3% from other tree products (Rohadi *et al.* 2011).

Locations of major smallholder teak systems in Indonesia — Figure 1



Map: Elissa Dwiyanti

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In Thailand and Laos, teak is also a component of integrated perennial-annual systems which reduce risks, diversify production, and raise income for smallholder families. Those systems transform barren and swidden land into tree cover, reducing labor needs compared to annual cropping systems (Mittelman, 2000; Midgley *et al.,* 2007; Newby *et al.,* 2012). Teak and other tree farming systems enable households to pursue off-farm opportunities (Newby *et al.,* 2014), including temporary migration to and employment in urban centers (Roshetko *et al.,* 2008). While demand for teak is high and prices attractive in Southeast Asia, many farmers needed assistance to adopt teak cultivation due to their limited capital, limited technical capacity, and limited market knowledge.

In dry ecosystems of Benin (Aoudji *et al.,* 2011), Togo (Kenny *et al.,* 2014), and Nigeria (Osemeobo, 1989) teak competes with agricultural crops and household land and labor are scarce. Yet smallholders are willing to grow teak on short-rotations to rehabilitate soils, diversify crop production and increase incomes. In the humid American tropics, specifically Panama (Zanin, 2005) and Costa Rica (De Vriend, 1998), biophysical and market conditions make teak cultivation an attractive option for farmers. However, to avail those opportunities farmers require support to access land, technical and market information, and quality planting material.

5.2.3 Production and Silvicultural Systems

In Central Java, farmers cultivate teak in four systems: kitren, tegalan, pekarangan, and line plantings. Kitren are teak dominated woodlots. Tegalan are mixed upland systems of trees and annual crops. Pekarangan are home gardens, with annual crops cultivated in the understory. Line plantings can be borders or across annual cropping systems. Farmers generally have more than one teak system or parcel. Tegalan are the most common and largest, accounting for half of the teak systems and averaging a half ha. Kitren accounted for a quarter of the systems, averaging a third ha. Pekarangan also accounted for a quarter of the systems, but are smaller, of a quarter ha. Kitren have the highest tree density and the least species diversity (Table 1). Home gardens have the greatest species diversity. Teak accounted for 55.9% of the trees (Figure 2) and 47.2% of the regeneration across all systems.

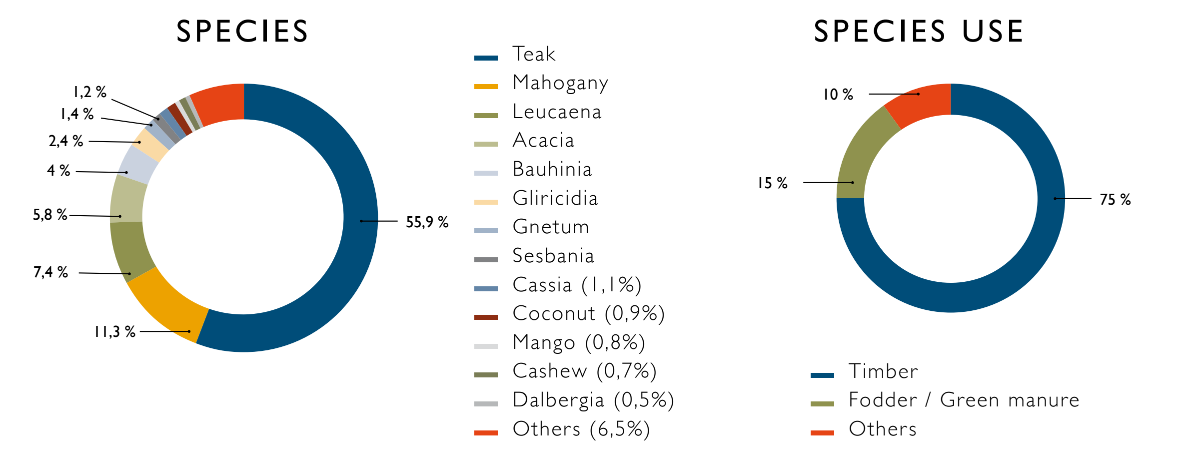
Most farmers (82%) manage their teak systems for both tree and annual crop production; over half of tegalan

Types and composition of smallholder teak systems in central Java. Table 1

Teak system	Percent of teak systems	Farm size (ha)	Tree density (trees/ha)	Number of tree species (system)
Tegalan (intercropping)	50.6%	0.47	1072	8
Pekarangan (home garden)	21.9%	0.24	1177	13
Kitren (woodlot)	21.9%	0.31	1532	5
Line plantings (agric. land)	4.8%	0.31	138	7

Source: Roshetko et al. 2013

Species composition of smallholder teak systems in Central Java Figure 2



and one-third of home gardens are intercropped annually. Kitren may also be intercropped. The most common intercrops are cassava, peanuts and upland rice, with soybeans, long beans and other vegetables also cultivated. The traditional Indonesian intercropping practice is called *tumpangsari*. It differs significantly from the taungya system where seedlings are intercropped with annual crops for 1-3 years to improve plantation establishment and early growth of trees. Tumpangsari is not limited to the tree establishment phase but is practiced with trees of all ages. It is a crop production and income generation strategy. Decisions regarding when and what to intercrop are based on prevailing market prices for agricultural crops, and available household labor and capital. The positive impact on tree growth is a welcomed benefit, but not considered in decision making (Roshetko *et al.,* 2013).

Smallholder teak systems in Indonesia have been described as overstocked, slow growing and of sub-optimal quality and production (Roshetko and Manurung, 2009). Initial tree spacing is 2.5x2.5 m to 3x3 m. These spacings are appropriate, if thinning is implemented on five-year cycles to reduce densities as trees grow (Pramono *et al.,* 2010; Pramono *et al.,* 2011). However, most farmers are reluctant to thin as the removal of trees is considered a loss of future income. Farmers' thinning operations are generally harvests that remove the best quality trees. Pruning is implemented to harvest branches for fuelwood, leaving behind branch stubs of 10-15 cm. Coppice is commonly used by farmers (20%) to establish a second rotation, but coppice thinning is not practiced. Few farmers (12%) have used improved quality germplasm to establish teak systems, most rely on wildlings (72%) or local seedlings (30%). Weeding and fertilizer application are only practiced in association with intercropping (Roshetko *et al.* 2013).

Poor silvicultural management of smallholder teak systems is also common in Laos (Midgley *et al.* 2007; Newby *et al.,* 2012), in Thailand (Mittelman, 2000), in Panama (De Vriend, 1998; Zanin, 2005), and for smallholder teak systems in general (Bhat and Ma, 2004). Similar to Indonesia, farmers in Laos (Midgley *et al.,* 2007), Panama (Zanin, 2005) and Togo (Kenny *et al.,* 2014) primarily use wildlings or local seedlings of unknown origin to establish their teak systems.

Participatory on-farm trials in Indonesia demonstrate that silvicultural treatment has enhanced growth of smallholder teak systems. Over a 2-year period, thinning and pruning treatments increased incremental diameter breast height (dbh) by 60% and incremental tree height by 124%. Coppice thinning increased incremental dbh by 45%. Recommendations suggest thinning should occur in 5-6 year-old stands to reduce tree density to 625 per ha. If initial spacing is 3 x 3 m or 2.5 x 2.5 m, the appropriate thinning intensity would be 40% and 60%, respectively. Pruning to 60% of total tree height is recommended also when trees are 5-6 years old (Roshetko *et al.,* 2013). Intercropping was also found to improve diameter increment and is recommended when crop production is supposed to be profitable.

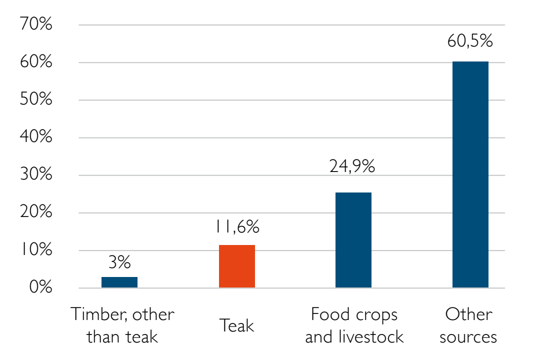
Based on the trials and related extension activities, local farmers recognized the advantage of silvicultural management. 70 % of the participating farmers and 30% of the non-participating farmers on the project site adopted some silvicultural practices (Rohadi *et al.,* 2011). Farmers with access to larger areas of land, higher on-farm income, and more assets are more likely to adopt silvicultural management (Sabastian *et al.,* 2014; Kallio *et al.,* 2011). Farmers with less income and small landholdings are more cautious and less able to shoulder the risks involved with a change of management. Involvement with farmer groups, access to information, and education level often enhance farmers' ability to adopt new (silvicultural) practices by expanding their knowledge.

5.2.4 Finance, Economics, and Marketing

Smallholder farmers have limited capital and household labor. They deploy those resources to generate the best returns with emphasis on the short-term. Teak is not prioritised. Farmers do not take loans to finance the establishment or management of tree farming systems; neither are private nor government banks interested to provide loans for smallholder timber production (Rohadi *et al.,* 2011). Fortunately, the cash costs to develop smallholder teak systems are generally low. As stated, most farmers depend on self-sourced local germplasm to establish teak systems. Fertilizers and weeding costs are only incurred with cultivating annual crop. Planting and other tree management activities are conducted when opportunity costs are low for other on-farm or off-farm activities (Perdana *et al.,* 2012). Similar finance approaches to smallholder teak production are reported in Laos (Newby *et al.,* 2014).

Farmers' limited investment approach is reasonable, as rotation ages are long and tree crops are not a main source of household income. Cash investment is only marginally profitable, partially due to limited market incentives and restrictive government policies (Perdana *et al.*, 2012). The contribution of teak to household income is only around 11.6%. The share is significantly greater

Contribution of teak sales to household income. Figure 3



Prices for smallholder teak in Gunungkidul district, Yogyakarta. Table 2

Age (year)	DBH (cm)	Price accepted by farmer (USD/standing tree)	Log volume after processing by traders (m^3)	Log price collected by traders (USD/m^3)
10	12–18	3–6	0.045–0.189	3–25
15	13–31	5–30	0.060–0.515	6–123
20	21–45	10–265	0.307–1.061	57–284
25	29–49	20–296	0.320–1.321	54–329

Source: Roshetko et al. 2013

than for other tree species such as mahogany (*Swietenia macrophylla*) and sengon (*Paraserianthes falcataria*) (3.0%), but far below the income generated from food crops and livestock (24.9%) (Figure 3). Farmers generally cultivate teak as living saving accounts where teak is harvested to finance significant cash needs such as weddings, school fees, large medical expenses, social commitments or emergencies (Perdana *et al.,* 2012).

Value-chains for smallholder teak in Indonesia include farmers, local traders, large-scale traders (wholesalers), and processors. The farmers' role is limited to producer. Standing trees are the standard unit of sale for farm-grown teak. Price negotiation is based on individual or blocks of trees. Negotiation is done without clear quality or value standards. The market rewards larger trees with higher prices (Table 2), but few farmers harvest trees based on economic maturity.

Both farmers and traders are motivated by higher prices for higher quality timber. However, most farmers are price takers. When selling timber, most farmers seek market information from other farmers who recently sold trees or improve their negotiation position by offering the trees to more than one buyer. But regardless of the approach taken, farmers usually obtain prices that are well below market rates because of their limited access to market information and weak negotiating position. Traders also face challenges, where they manage various activities, such as the physical possession and ownership of teak logs, promotion to potential buyers, negotiation with buyers and smallholders, attending to government permits, and risk of possible loss and quality of product over time. Traders also provide financing related with debt bondage to farmers who are willing to use their trees for mortgage. Each activity represents costs that may not be recovered for various reasons (Perdana and Roshetko, 2015). These activities resulted in high risk and high transaction costs, leading to lower prices for farmers.

5.2.5 Recommendations and Guidance

Smallholder teak systems enable farmers to diversify farm production, reduce risk, support food security, and generate income. They are also an important alternative source of quality timber for the teak industry. Unfortunately, the potential of smallholder teak systems is limited by poor silvicultural management, limited market access, and policy disincentives. These impediments must be addressed.

Smallholders' tendencies in some countries to manage and harvest teak to meet their financial needs has an important function as part of their social and economic safety net. However, silvicultural management of smallholder systems requires improvement. Chief among these is the adoption of thinning to enhance incremental diameter growth. While specifics may vary by location, the following is provided as a general recommendation. When plantings are 5-6 years old, they should be thinned to 625 trees per ha. To overcome farmers' reluctance to thinning, plantings can be established with alternating rows of teak and a short-rotation timber species (e.g. *Gmelina arborea*, *P. falcataria*) that can be harvested in 5-8 years. Similarly, pruning to 60% of total height is recommended for 5-6 year old trees. Subsequent thinning and pruning should be considered on a 5 year basis. As intercropping generally has a positive influence on tree growth, intercropping is encouraged with crops that meet local market demand. Most important, trees should be retained until the age of 20 to 30 years, when they reach a diameter size that is compensated with a lucrative market price.

Limited market access greatly hinders farmers' incentive to produce quality teak. A shared-value model, which is a business strategy focused on creating economic value in a way that also creates economic value for farmers, would improve the knowledge of teak farmers and local traders. These interactions could be further expanded to become farmer-industry partnerships where farmers produce trees to meet market specifications. Farmers could engage in group marketing to reduce transaction costs and improve timber supply.

Governments could provide incentives to smallholder teak farmers, and indirectly to the teak industry, by simplifying timber trade regulations to minimize transaction costs and eliminate extra-legal fees. They could also regularly publish market information on teak prices and quality. Government and support agencies can provide silvicultural training and extension services to enhance smallholders' technical knowledge and capacity. With research agencies and industry, they could facilitate farmers' access to sources of quality germplasm.

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CHAPTER 6
Wood Quality for Advanced Uses of Teak from Natural and Planted Forests

P. K. Thulasidas[18] and Henri Baillères[19]

6.1 Summary and Conclusions

Teak is preferred for its high quality timber owing to its moderate density and strength, high dimensional stability, high durability and ornamental wood figure. The key wood characteristics are linked to the heartwood formation. Considering the declining supply from natural forests, the long-term prospects of short rotation plantation-grown teak seem promising, and the following factors are considered relevant in terms of end-use.

- The wood properties such as colour, grain, texture, wood density etc. of teak from young plantations are slightly different and fetch lower prices in the market than the naturally grown teak or plantations of 50-60 years.
- Enough evidence is available from different parts of the world to show that plantation-grown small dimension teak is not inferior to natural teak of the same age in terms of density, strength and shrinkage.
- After log geometry and knottiness considerations, profitability is substantially influenced by the proportion of sapwood.
- Heartwood percentage increased with growth rate of trees with increasing DBH and the effect of growth rate on the heartwood-sapwood ratio seemed to decline with age. Consequently, it is possible to produce large diameter logs with greater proportion of durable heartwood per tree by accelerating tree growth through silvicultural interventions in short rotation plantations.
- The colour of heartwood is an important wood characteristic for commercial products and can be controlled by a suitable genetic selection.
- Higher natural durability and stability of teakwood is reflected in higher extractive content. Fast-grown teak is generally less durable than mature teak due to a lower amount of extractives.
- By adopting simple colorimetric methods and extractive content assessment (e.g. through NIRS), durability can be assessed for plantation teak at young age.
- In order to obtain highly durable teakwood for special products and for external applications, it is advisable to retain the teak trees for longer rotations of 50-60 years or more, disregarding short-term investments and benefits. Genetic improvement may overcome the need for long rotation since the variability in extractive content could be controlled through judicious selection strategies.
- A combination of appropriate site selection coupled with good germplasm material and by adopting the right silvicultural practices could increase the yield to 8-10 m^3/ha/yr that will be realistic on a short rotation of 20 years for better economic returns.
- Teak exhibits wide variations in wood quality traits and within-tree variations are greater, rather than between populations; this characteristic of within tree-variations has to be taken into consideration for tree improvement.
- Matching the provenances for specific site conditions (site matching) and product requirements appears to be most crucial in tree improvement programmes.
- Existing grading systems for teak timber need to be reviewed and changed as necessary, taking into consideration the quality and dimensions obtainable from plantations as well as from natural forests.
- Standardised internationally accepted log grading rules and volume measurements should be followed for the trading and marketing of teakwood.
- National and international agencies should strive to promote best practice in teak cultivation and

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management, especially to ensure the ability of small-scale growers to manage wood lots sustainably, to access markets and to make profitable returns for their livelihoods.

6.2 Introduction

Teak is sometimes referred to as the queen of tropical hardwoods and according to 19th century German botanist Sir Dietrich Brandis, "...among timbers, it holds the place which the diamond maintains among precious stones and gold among metals." The quality performance of teakwood expected from fast growing planted teak is high because of the high demand for wood accompanied by the log export ban on naturally grown teak. In this context, it is important to add value to the timber of planted teak by improving the wood quality through genetic selection, silvicultural control and processing techniques. There are marked variations in wood properties of fast-grown teak coming from various locations across the tropical regions with noticeable differences in genetic origin, growing conditions and silvicultural practices. The present paper is an attempt to synthesise almost three decades of research conducted on wood quality from teak plantations. It is also the goal of this work to analyse the factors that influence key wood properties and their variations in order to suggest relevant strategies for the future production and processing of short-rotation teak. Advanced approaches to improve the utilisation of small dimensional teak logs for a variety of end products will be raised.

Figure 1

Graded plantation teak logs, Nilambur, India
Photo © P. K. Thulasidas

6.2.1 Wood Properties of Natural Teak

The unrivalled quality of teak wood is essentially due to a unique blend of key elements; it combines relative lightness (medium density), very high durability to biological and physical agents, exceptional stability, high level of mechanical properties and appealing aesthetical features. British craftsmen have used teak in traditional high-end garden furniture since the 18th century and teak benches built over a century ago still grace London's gardens from Hyde Park to Kew. For centuries, teakwood has been traded according to the place of origin like Burma-teak from Myanmar, Siam-teak from Thailand, Malabar-teak from India (Fig. 1) or Java-teak from Indonesia. The wood quality has been said to be dependent on the geographical origin of the wood. In the past, four types of teak wood qualities were described based on wood figure, roughly ranging from dark wavy brown coarse grain to straight yellow tight grain. The naturally grown teak from Burma is of a uniform golden-brown colour without markings but most other teak is rich brown with darker chocolate brown streaks. Indian teak is straight or wavy grained and mottled and oily to the touch. It is marked with white glistening silica deposits.

Teak has been the logical material for the construction of the most engineered and exposed structures such as high performance vessels. It has been used in a very wide range of products such as beams, plywood and decorative face veneer, moulding, strip and block flooring, furniture components, solid doors and flush doors, door and window frames and shutters, laminated boards and panels, carved articles, household utensils and kitchenware, etc.

The *intrinsic* wood property of teak that distinguishes it from other timbers is due to the presence of various active extractive elements encrusted on the cell wall. Some are poisonous to invading termites and fungi; others have hydrophobic properties (water repellent properties) due to the high content of specific lipids (Rudman and Da Costa, 1959; Premrasmi and Dietrichs, 1967; Yamamoto *et al.*, 1998). In the heartwood the total extractive content varies from 10% to a maximum of 19.8% (Sandermann and Simatupang, 1959, 1966; Thulasidas and Bhat, 2007). At an average wood density of 650 kg/m^3 the most outstanding characteristics of teak, however, are its durability and high resistance to water absorption, hence its wide use in ship and boat building for decking, rails, and hatches. Another unique property is its outstanding technological resistance to abrasion and iron stains.

6.3 Quality Concerns of Planted Teak

Teak has been identified as the most potential species for establishing high-quality tropical hardwood plantations under sustainable forest management (Bhat and Ma, 2004). Production of high quality wood in relatively long rotations of 50-70 years in forest plantations has been the traditional practice ever since the world's first commercial teak plantation was established at Nilambur in India's Kerala state in 1842. On suitable soil longer rotations produce large size logs with generally better quality timber having highly durable heartwood. They therefore attract higher market prices. However, longer rotations also involve longer gestation periods for return of investments. Shorter rotations of 20-30 years or even 10-20 years for both veneer (sliced) and saw log production for relatively quick returns are now being practiced in many tropical countries of the world (Ball *et al.*, 2000, Pandey and Brown, 2000; Pérez, 2005). Teak is encouraged on the basis of exceptional market demand and the high prices it fetches in the international market*. Growth in intensively managed teak plantations is anticipated to be quite fast in the initial few years of growth (Bhat *et al.*, 2001a). The mean annual increment (MAI) reported from such fast-growing plantations appears to be modest to the tune of 7-10 m3/ha/yr except for Central and Latin America where most of the plantations are managed by the private sector (Kollert and Cherubini, 2012). In some countries like Laos the average rotation is around 10-12 years. With such short rotations from various genetic materials often of poor quality, there has been mounting concern over the past 2-3 decades regarding the technical performance of teak compared to the renowned quality standard of teakwood from traditionally managed forest plantations. In this context, it is necessary to better understand how the technological performance of teak timber can be impacted by intensive silvilcultural practices often combined with very short rotation.

6.3.1 Factors Influencing Wood Quality

Wood quality as defined by traders and end-users is often solely dependent on visual appearance, i.e., colour, grain and texture that constitutes the wood figure and the defects. Tree size alone does not affect wood quality, but it often acts as a surrogate for other quality attributes, such as the proportion of heartwood/sapwood, and the amount of clear wood produced. Larger tree size generally makes harvesting, transporting, and sawmilling more efficient. There exists a common myth that faster growth invariably results in lower wood density. However, genetic studies on teak have shown no significant relationship between growth rate and wood density, and also with stem diameter (Sanwo, 1986). The other major structural factors that influence the market value of timber are the physical and mechanical properties, anatomical characteristics and the biological properties as detailed by Baillères and Durand (2000) in Table 1. These properties are affected by silvicultural treatments, site conditions, and by genotype x environment interactions. High variability of plantation wood is common, often caused by poor silvicultural practices and insufficient pruning (Baillères and Durand, 2000). Bhat (2000) summarized

Wood quality factors related to technological characteristics — Table 1

Wood quality factors	Wood properties	Remarks
1. Aesthetic properties	■ Colour ■ Grain ■ Texture	The three parameters constitute the wood "Figure"
2. Physical	■ Shrinkage ■ Ratio tangential /radial shrinkage ■ Absorption properties (fibre saturation point)	In three different directions of wood structure An anisotropic ratio indicating dimensional stability Link to dimensional stability
3. Mechanical	■ Modulus of Elasticity (MOE) ■ Modulus of Rupture (MOR) ■ Maximum crushing stress (MCS) ■ Hardness ■ Growth stresses	Correlated with specific gravity and Microfibril Angle (MFA) The pith to bark variations of these properties indicate the juvenile stage or the maturity state of wood
4. Geometrical	■ Heartwood/sapwood ratio ■ Bole shape ■ Knots characteristics	Important as it is directly related to timber recovery (i.e., sawn timber grades recovery)
5. Biological	■ Decay resistance ■ Insects resistance ■ Weather resistance	Representing the natural durability that is mostly linked to extractive content and activity

Source: Baillères and Durand, 2000

* From 615 USD/m^3 reaching 1000 USD/m^3 for Myanmar natural teak. For plantation teak there is slow increase from 300 USD/m^3 to 430 USD/m^3 (Unit price of teak round wood imports to India, 2005-2014) Kollert and Cherubini, (2012).

findings which showed that young trees (13-21 years of age) are not necessarily inferior in wood density and strength compared to older trees (55-65 years), and rotation length of fast-grown teak can be reduced without compromising timber strength (see Table 3).

Wood property data derived from a series of African plantations and from some natural stands in Asia (Baillères and Durand, 2000) show that:

1. In general, teak wood from African plantations is not necessarily inferior to the one coming from naturally grown teak; its quality is quite similar.
2. There is a great variability within each wood characteristic presented among plantation-grown teak: one can find the worst quality as well as the best sometimes on the same site if various genetic materials have been planted.
3. This variability is not clearly linked to specific sites.

Obviously, these remarks cannot be generalised to all plantations worldwide. For example, substantial differences exist between the appearances of wood coming from different seed sources. The reasons of such variations are not well known, it seems, however, that, besides the genetic and silvicultural effects, the climate would have a significant effect on some characteristics. Results from wood property analysis from a series of clones from diverse origins growing on the same plot exhibit highly contrasted performances. This suggests a substantial impact of the genetic origin on key technological properties (Chaix *et al.*, 2007, 2011).

6.3.2 Log Grading and Volume Measurements

A lack of standards and consistency in establishing prices for teak logs has been a long-standing and common theme of discussions of international teak markets. In the Regional and World Teak Conferences held in 2009, 2011, 2013 and 2015, several expert observers voiced serious concern about the lack of international log grading rules applicable to both producer and purchaser countries. Most countries and regions have their own set of specifications and grading rules which differ for various species of softwoods and hardwoods. The Asia-Pacific regional grading rules for teak logs have been published by FAO in 1959 and Myanmar's export of natural teak was following the Grading rules for teak veneer logs prepared by the Myanmar Timber Industry Board (1964). In India, grading rules for teak logs and squares are being practiced as per the Bureau of Indian Standards (1968, 1976). The creation of uniform international log grades for plantation teak, along with standardized lumber and product grades would be of great help to improve the marketability of teak wood products. Standardized descriptions are needed so that buyers know the exact quality of the products being offered for sale (Ladrach, 2009). Recently, Hopewell *et al.* (2015) have proposed a guide for log and squares grading in order to provide a fair price for logs and squares, establishing a clear understanding of what the buyer is paying for.

There is no single internationally accepted method for measuring logs which can allow reliable comparison of prices between countries. Log volumes can be calculated in several ways, each offering a legitimate (but different) result. FAO (2010) offers a practical example of the importance of adopting agreed conversion factors: the stand volume may be reported in cubic meters over bark but the purchaser may need to convert these volumes into inside bark volumes, weight or board feet to match their units of measure. Countries like India (the world's largest teak market) follows the Hoppus system (Quarter girth formula, $V = (G/4)^2 \times L$, where 'V' volume in cubic meters and 'L', length in meters) is used. A standard 20' container can hold up to 15 m^3 (real volume) of small logs, but this may convert to about 13 m^3 when the Hoppus system is applied (in India) and this can cause considerable confusion. Hence, there is an acknowledged need for producers and buyers to agree on a common form of log measurement or to standardize allowances or agree on standard conversion factors to convert volume to true cubic volume (Midgley *et al.*, 2015).

6.3.3 Heartwood – Sapwood Proportions

In the intensively managed short-rotation plantations in the tropics the aim of the plantation managers is to produce maximum volume of heartwood with reduction on non-durable sapwood. Heartwood initiation in teak trees start at the age of 4-5 years (Bhat, 1998). The amount of heartwood varies considerably with age, site and growth rate, and between families, genera and species (Hillis, 1987). A review of heartwood properties of teak from fast-grown plantations has been published recently by Moya *et al.* (2014). In teak, heartwood percentage increased with growth rate of trees with increasing diameter

Figure 2

Typical heartwood shape in a 10-yr-old fast growing planted teak. Photo © H. Baillères at breast height (DBH). The effect of growth rate on the heartwood-sapwood ratio seemed to decline with increasing age, resulting in negligible differences between fast and slowly-grown mature trees aged 55-65 years (Bhat, 1998). The same trend was recorded for teak from Costa Rica, increasing logarithmically with increasing age and consequently with DBH (Pérez, 2005). Faster growth in plantation-grown teak in Nilambur, India, at age 8-years does not affect wood density, however, the percentage of heartwood has increased considerably (Bhat, 1995).

The heartwood proportion in teak depends not only on the age, but also on the ecological zones in which the tree grows as observed by Kokutse *et al.* (2004) for teak in the range of 40-45 years. In a study on 35- yr-old home-garden teak at two locations in India, Thulasidas and Bhat (2009) reported no significant difference in the heartwood-sapwood proportion, even though the large diameter logs had a proportionately higher heartwood percentage than small diameter logs. With judicious fertiliser application on the appropriate site and with silvicultural management, increased diameter growth can result in a high proportion of durable heartwood in intensively managed teak plantations. The sapwood proportion decreased with age and stabilises at maturity, thereafter maintaining a constant width with the proportion of heartwood (Table 2).

Sapwood yield from short-rotation plantations is considerably higher, adversely affecting the durability of timber unless the material is adequately treated with environmentally-friendly preservatives. With higher penetrability, sapwood is easier to treat with preservatives than the refractory heartwood. However, the transition zone, which is very light in colour, is often quite difficult to treat due to low liquid permeability. A high proportion of sapwood is a real concern for outdoor furniture (Fig. 2). In producer countries of short-rotation plantations, the felled small dimensional logs are chipped on its four sides at the primary log processing yard to remove bark and sapwood partially. The fresh green squared logs are often loaded into containers and exported. In most Latin American countries and several Asian countries, a majority of current sales are made in rough squares or flitches (Ugalde, 2013, Figure 3).

Figure 3

Small dimensional teak squares in a primary log processing yard in Ecuador, 2015. Photo © P. K. Thulasidas

During this 'squaring of logs' the outer bark with sapwood was partially removed and offers value to the buyer, facilitates easy loading and efficient transport by container. Apart from possible damage to wood quality, insects and fungi can present phytosanitary problems requiring expensive quarantine procedures.

6.3.4 Juvenile Wood in Teak

Wood processing industries are compelled to learn to utilise the small timber resources coming from fast-grown teak plantations. As the short-rotation plantations are felled at the age of 20-25 years, large volumes of juvenile wood containing a substantial amount of sapwood are traded

Table 2

Dimensions and percentage of heartwood and sapwood at breast height (BH) level in selected fast grown trees sampled at various ages from Nilambur, India.

Age (yr)	Heartwood		Sapwood	
	Diameter (cm)	Percentage	Thickness	Percentage
13	12.6	58.3[a]	1.9	41.7[a]
21	16.8	65.0[b]	2.1	35.0[b]
35	31.0	72.8[c]	2.2	27.2[c]
55	38.8	85.1[d]	1.7	14.9[d]
65	39.6	87.8[d]	1.4	12.2[d]

Figures with same alphabet letters in superscript are statistically non-significant
Source: Bhat, 1998; Thulasidas and Bhat, 2009

across international markets. The problems commonly associated with juvenile wood phases are excessive longitudinal shrinkage, warp and reduced strength with lower wood density (Senft, 1986). Juvenile wood (immature wood) is formed in the initial few years of growth, roughly in the initial 15 or 20 growth rings or cambial age, and the anatomical, chemical and physical properties significantly vary in the younger trees. It is important to note that these properties gradually change from initial juvenile to mature characteristics during the juvenile phase. When the mature state is reached, these characteristics only vary moderately. As a consequence the juvenile wood is actually a zone with steep gradient of properties along the radius of a log. The general notion prevailing among teakwood users is that fast-grown teak produces only light, weak and spongy wood. On the contrary, the recent findings by Bhat and Indira (1997) and Bhat (1998) reveal that the trees selected for fast growth in forest plantations of different ages (13, 21, 55 and 65 years) mostly display non-significant differences with regard to density and strength properties, Young's modulus (MOE), modulus of rupture (MOR) and maximum crushing stress (MCS). Bhat *et al.* (2001b) determined the demarcation between juvenile and mature wood in a 65-yr-old teak plantation in India for assessing the utilisation potential of short rotation timber. While MOR and MOE of fast-grown (phenotypically superior) trees were significantly lower in juvenile wood phase by 20-21%, MCS of both fast- and slowly-grown trees did not differ between juvenile and mature wood. They also reported the maturity age of teak lies in around 20-25 years. Enough evidence is available from different parts of the world to show that plantation-grown small dimension teak is not inferior to natural teak in terms of density, strength and shrinkage (Bhat, 1999, Bhat *et al.*, 2005; Thulasidas and Bhat, 2012) of trees of the same age. Teak can attain optimum strength properties in 21 years of age as recorded from Nilambur, India (Bhat *et al.*, 2001b), as illustrated in Table 3.

However, as mentioned previously, it is important to note that the juvenile wood is generally less durable. As the formation of the heartwood is controlled by a secondary metabolism mechanism, not by the cambial activity, special attention should be given by researchers to the quantitative and qualitative formation of the heartwood.

Figure 4

Uniform golden brown colour of heartwood of Nilambur teak, India. Photo © P.K. Thulasidas

A further source of variation is the presence of tension wood formed in an effort of the trees to stand straight or to lean in a more favourable position resulting in pith eccentricity. The technological characteristics of juvenile wood and tension wood are notably different with respect to 'normal' mature wood. Consequently, care should be taken in silvicultural regimes to minimise the production of tension wood and when sawing and processing young fast-growing trees which may contain a high proportion of juvenile wood and often zones of tension wood. Training programmes are needed to improve skills and productivity and to reduce waste in the processing of small dimensional teakwood, including sawing and drying, but also in the other value-addition processes, such as the design and manufacture of fine furniture and marketing strategies of these less durable but attractive teakwood products.

6.3.5 Heartwood Colour

Colour is one of the quality criteria of wood to assess its suitability for certain end-uses such as furniture and decorative veneers. Wood colour influences prices and

Strength property variation among five age groups of teak from Nilambur, India Table 3

Property	Age (years)					Natural teak
	13	21	35	55	65	65
Specific gravity	0.63[a]	0.63[a]	0.63[a]	0.64[b]	0.64[b]	0.64[b]
MOE, N/mm²	11468[a]	14129[b]	9709.9[a]	10564[a]	12335[a]	12530[a]
MOR, N/mm²	108[a]	134[b]	111.2[a]	104[a]	100[a]	106[a]
MCS, N/mm²	49[a]	56[b]	60.6[b]	51[a]	59[b]	60.4[b]

(Age groups with similar alphabets in superscript display non-significant differences)
Source: Bhat, 1998; Bhat et al., 2008; Thulasidas and Bhat, 2012

Black streaks on the cross-sectional surface resembling growth rings (left) and the decorative black streaks on the flat-sawn surface Photo © P. K. Thulasidas

Figure 5

even slight differences in heartwood colour would yield the product a different value. Precise colour description is essential for evaluation of aesthetic quality of wood products. The CIELab system is the most common colorimetric method used for providing accurate and objective colour measurement. Natural grown teak has a distinct colour transition from sapwood to heartwood characterised by a golden brown colour (Bhat, 1999, Fig.4) and heartwood colour of fast-grown teak is notably variable (Moya and Berrocal, 2010). Wood from fast grown teak trees is less durable than natural forest teak trees (Bhat and Florence, 2003) and the wood is generally paler and lighter (Thulasidas and Bhat, 2006; Kokutse *et al.*, 2006, 2010). The paler colour is associated with less durability due to a low amount of extractives. Other important differences between plantation teak and natural teak are the irregular display of decorative black streaks along the annual rings in the heartwood of plantation trees and the resulting beautiful figure in the flat-sawn surface (Nobutchi *et al.*, 1996; Lukmandaru *et al.*, 2009, Fig. 5). Wood of this type was available from drier areas with low rainfall and the log dimensions were small (Thulasidas and Bhat, 2006), also on deeper, fertile sites (Moya and Calvo-Alvarado, 2012).

Despite the small dimensions, such type of wood has great potential in the furniture industry as it achieves higher prices in the market. But for decorative interior panelling, lighter coloured wood is being preferred in Europe and USA (Suhaedi, 1998). Environmental factors had a stronger effect on the colour of teak heartwood than the age of stand, and fertile plantation sites showed a tendency towards darker and less red heartwood (Derkyi *et al.*, 2009). The colour of heartwood is an important wood characteristic for commercial products and can be controlled by a suitable genetic selection (Moya and Marin, 2011). It is important to note that the sapwood colour is not correlated with the heartwood colour, and as a consequence it is not possible to predict the heartwood colour from sapwood colour analysis.

6.4 Natural Durability and the Controlling Factors

In general, teakwood belongs to durability class I (highly resistant timbers) as assessed by the international standard classification (ASTM, 1981). Fast-growing conditions generally do not significantly jeopardise timber strength (Bhat and Indira, 1997; Bhat, 1998, 1999); however, the wood from such plantations is often less durable (Bhat and Florence, 2003, Bhat *et al.*, 2005). Durability is largely determined by the various polyphenolic compounds (extractives) encrusted on the cell wall and other anthraquinone and naphthoquinone derivatives which offer various degrees of decay resistance to teak timber. Teak heartwood is termite resistant due to the presence of tectoquinone (about 1%) and contain 3% caoutchouc (antioxidant compound) ascribed to the relatively high incidence of water repellence and oily feel of teakwood surface. The alliance of toxic and water repellent compounds is the basis for the exceptional durability and stability of teak wood. The quantity of total extractives as an indicator of natural durability and dimensional stability of teak has been established by several authors (Rudman and Da Costa, 1958, 1959; Sandermann and Simatupang, 1966; Myo Aung, 1988; Simatupang *et al.*, 1996; Yamamoto *et al.*, 1998; Bhat *et al.*, 2005; Thulasidas and Bhat, 2007; Moya *et al.*, 2010). This parameter is globally highly dependent on the age of the tree. As the tree ages, durability also increases. High durability of teakwood is due to the higher extractive content, the durability increases radially from pith to the outer heartwood. The juvenile wood found near the pith offers less durability and the wood is often spongy and lighter. Of late, it was reported that more than the total extractive content, the individual chemical compounds, even if present in small quantities, offer durability to teak heartwood (Haupt *et al.*, 2003; Windeisen *et al.*, 2003; Thulasidas and Bhat, 2007; Sumthong *et al.*, 2008). Overall, it is the synergetic effect of all these factors which gives teakwood the adequate protection against wood decaying organisms, hydrophobicity and dimensional stability. The total extractive content, as determined by classical extraction procedures, provides sufficient evidence on decay resistance and dimensional stability of the wood.

In order to obtain highly durable teakwood for speciality products and for heavy-duty external applications, it is advisable to retain the teak trees for 60 years or more, disregarding the short-term investments and benefits. Even with the good germplasm and fast-growth rates observed in the Pacific and in Latin America, teak does not reach maturity until 20-25 years of age, so wood harvested from most of these plantations reaching the market are not durable enough to use it confidently for exterior applications. Judicious genetic selections to enhance the quality of the juvenile heartwood of logs for durability and stability will be a clear competitive advantage in the near future.

6.5 Breeding for Wood Quality

Since teak has a remarkable broad natural occurrence, from West India to North Laos down to South Indonesia (where it is naturalised), it is not surprising that the various genetic origins available are adapted to specific conditions (climate and soil). As a consequence a judicious choice of the genetic material for a given site is a key element for increasing the value of the resource. This explains the huge variation in wood quality from the plantations around the world, from the best to the worst. As a result genetic (covering the entire natural occurrence) and site matching should be the focus of future research. The selection criteria should be based on the value mixing recovery and wood quality (heartwood characteristics should be on the top of the list).

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CHAPTER 7
Economics, Production, Markets and Trade

7.1 World Teak Resources, Production, Markets and Trade

Walter Kollert[20] and Przemyslaw Jan Walotek[21]

7.1.1 Summary and Conclusions

References. This chapter provides a concise summary of the most recent studies and reports on world teak resources, production, markets and trade, all of which are available online on the Internet[22].

Resources. In 2010 the area of natural teak forests in India, Lao PDR, Myanmar and Thailand combined was estimated at 29.035 million ha, almost half of them growing in Myanmar (13.5 million ha). Since the 1980s, supplies of teak wood from natural forests have started to dwindle. Nevertheless, teak is an emerging valuable hardwood resource that has been grown increasingly in planted forests in about 70 tropical countries throughout tropical Asia, Africa, Latin America and Oceania. For most of these countries teak is an introduced species, but for them it represents the best opportunity to produce quality timber and is of major importance to their forestry economies attracting large investments from the private sector. Planted teak forests according to various estimates cover between 4.35 to 6.89 million ha.

Teak quality. The exceptional qualities of teak wood make it one of the tropical hardwoods most in demand for the luxury market (e.g. for yacht building), for applications in the construction industry (e.g. in India) and furniture manufacturing (e.g. in China), together with mahogany (*Swietenia macrophylla*), red cedar (*Cedrela odorata*) and Indian rosewood (*Dalbergia sissoo*). The good reputation of teak was built originally upon high-quality timber from natural forests. Wood from mature teak plantations above 50 years of age in India, Thailand and Indonesia can be commensurate with the quality of native teak. Most planted teak forests, however, are managed in short rotations of up to 20 years. Plantation-grown teak does not yet have a high-quality image on the international market, and it is questionable whether it will ever reach such quality standards given the trend to shorter rotation periods.

Production. Although the annual wood increment of planted teak forests is estimated at around 30 million m^3 (Midgley *et al.*, 2015), only 2.0 - 2.5 million m^3 are harvested annually from natural and planted forests. This production level is expected to increase, in particular from planted forests in Central and South America. In addition, some of India's large teak plantation estates, previously unavailable for commercial utilisation, may be made available to meet India's growing domestic demand.

Teak genetic resources. It can be expected in the future that the sustained production of teak logs from natural forests will be on a continuous decline due to increasing deforestation and the growing competition for

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environmental services. If natural teak forests and their genetic resources are to be sustained in the long term, it appears imperative to organise and implement a global program for the conservation of natural teak forests that is supported by all major international forestry institutions.

Trade. Between 2005 and 2014, the global annual trade of teak roundwood was more than 1 million m^3 on average; the imports were valued at US$ 487 million a year, which is about 3 per cent of the value of the global timber trade (US$ 15.5 billion). The three major importing countries were India, importing three quarters (74 per cent) of the total trade volume from more than 100 countries, followed by Thailand (16 per cent of the total from about 15 countries) and China (10 per cent of the total from about 65 countries). Teak imports to Thailand have declined considerably in recent years, from a peak of 6.7 million m^3 in 2004 to only 61 000 m^3 in 2014. China and India, on the other hand, have increased their import volumes.

Market constraints. The major challenge for teak growers is to produce quality wood that is acceptable in international markets. Despite considerable international dialogue over many years the global teak trade is hampered by a lack of standards and consistency in measuring and establishing volumes and prices for teak logs, which results in widespread uncertainty and confusion around teak investments. This is aggravated by the application of different methods of calculating log volume which can lead to misunderstandings and confusion. Units used in measuring log volume include cubic feet, cubic metres and board feet, average diameters, centre log diameter, small-end diameter and circumference. Of course, conversion factors enable movement between systems, but there is no international standard for conversion factors. The adoption of an agreed set of log grading rules in collaboration with global buyers would be a good start to improving the marketability of teak wood products (Midgley *et al.* 2015).

Certification. One increasingly important consideration influencing trade in plantation teak involves certification and the legality of logs. The large markets of North America and Europe have responded legislatively through the Lacey Act (USA) and the European Union Timber Regulations (EUTR). Governments, buyers and retailers, mainly in western countries have embraced the principles of certification. Legality is not an issue in all markets, however.

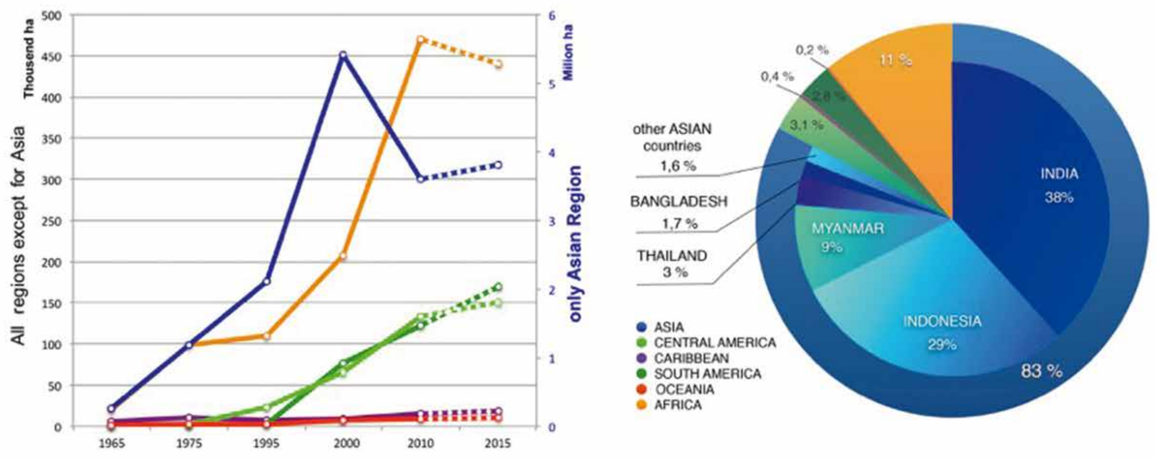
7.1.1 Teak Resources

In 2012, FAO published a global assessment of teak resources and markets which currently offers the most reliable single source to access global information on teak in spite of the fact that some teak growing countries did not report for this survey (Kollert & Cherubini, 2012). Myanmar, India and Indonesia are the teak 'heavyweights' at the global level. These three countries dominate the production of teak, as they hold more than 95% of the world's natural and more than 75% of the world's planted teak forests. In 2010, the area of natural teak forests in India, Lao PDR, Myanmar and Thailand combined was estimated at 29.035 million ha, almost half of it growing in Myanmar (13.5 million ha).

Planted teak is the only valuable hardwood that constitutes a globally emerging forest resource. The global area of planted teak reported from 38 countries in 2010 was

Area of planted teak forests by region

Figure 1



The scale on the left side of the line chart (thousand ha) applies to all regions except for Asia, while the scale on the right side (million ha) applies to Asia only.

Sources: Keogh, 1979; Tewari, 1992; Pandey & Brown, 2000; Kollert & Cherubini, 2012; Kollert & Walotek, 2015 calculated at 4.35 million ha, of which 83% grew in Asia, 11% in Africa, 6% in tropical America and less than 1% in Oceania (see Figure 1, right side). Taking into account the data missing from non-reporting countries, this figure certainly underestimates the actual area of planted teak forests in the world. The area of planted teak forests is substantial in India with reported 1.667 million ha (38% of the total), Indonesia with 1.269 million ha (29%) and Myanmar with 390,000 ha (9%). Since 1995, the planted teak area has increased significantly in Africa (e.g. Benin, Ghana, Côte d'Ivoire, Nigeria, and the United Republic of Tanzania), Central America (e.g. Costa Rica, El Salvador, Guatemala, Nicaragua, Panama), and South America (e.g. Ecuador, Brazil, Columbia).

Combined with other sources FAO's global assessment of teak resources 2010 allows for a tentative assessment of the development of planted teak forests since 1965 including estimates for the period 2010 to 2015 (see Fig. 1, left side). Based on the global teak trade survey conducted in 2015 (Kollert & Walotek, 2015) and the area statistics presented at the 3rd World Teak Conference 2015 we have estimated an expansion of planted teak forests since 2010 by more than 1 million ha to cover ca. 5.37 million ha in 2015. Asia maintains its dominant position regarding planted teak forests as compared to all other continents. Nevertheless the decline in area from 2000 to 2010 is remarkable, if we follow the statistical figures reported by different sources. We propose that this decline is due to an overestimation of the area in the 2000 survey (Pandey and Brown, 2000) and an underestimation in the 2010 survey (Kollert and Cherubini, 2012), when only 10 out of 16 teak producing Asian countries reported. As for Africa, industry sources suggest that the planted teak forest area in West Africa has declined since 2010, as many plantations have not been replanted (Midgley *et al.*, 2015) and the volume of roundwood exports from this region was substantial in recent years.

Midgley *et al.* (2015) estimate the area of planted teak forests at 6.89 million ha based on FAO and ITTO data. Considering that the authors always used the highest available figure published in these studies, we conclude that 6.89 million ha is likely the highest possible estimate of the global area of planted teak forests.

Planted teak forests are predominantly younger than 20 years. The prevailing age class distribution is an indication of increased efforts to establish and manage planted teak forests during the past 20 years and this pattern is very likely to persist in the future. The current enthusiasm by many corporate and private investors for planted teak will maintain the young age structure and, in order to improve the economic rate of return, will tend to shorten the rotation period. This will lead to a significant increase in the supply of small-dimension logs.

7.1.2 Teak Production

There are very few estimates of the total commercial teak volume harvested globally from natural and planted teak forests. Katwal (2005) estimated a global teak production of at most 1 to 1.5 million m^3 per year from planted forests. Based on more recent figures reported for FAO's Teak Resources and Market Assessment 2010 we can reasonably assume that a volume of ca. 0.5 million m^3 is harvested in natural forests, predominantly from Myanmar. The production of quality teak from natural forests in India, Lao PDR and Thailand is low as most of their natural teak forests grow within protected areas, which will not contribute in the future to meet the worldwide demand for teak wood. The production of industrial roundwood from planted forests is estimated at 1.5 to 2 million m^3, if all teak producing countries are accounted for. Hence, the world's teak supply from natural and planted forests adds up to 2 to 2.5 million m^3 yearly, of which at least 90% is cut in India, Indonesia and Myanmar. This estimate must be adjusted upwards to allow for illegal logging in natural forests and unrecorded harvesting by small farmers and local communities.

Global teak markets make a fundamental distinction between teak grown in natural and planted forests. Logs of native teak are usually considerably larger than those grown in planted forests, with a higher proportion of heartwood. Beyond the size advantage, strong market perceptions persist that native teak is superior to planted teak with respect to several properties, although research shows that these assumptions can be questioned when fitness for specific purposes is taken into account (Midgley *et al.*, 2015). Bhat and Ma (2004) report that plantation teak is unlikely to attract the high prices of premium teak from native forests.

Myanmar, India and Indonesia traditionally were the principal sources of native teak on a commercial level in international markets. However, the supply of quality teak logs originating from old-growth natural teak forests in Myanmar has declined as a result of the log export ban in force since 1 April 2014, as well as the declining harvestable area and the deteriorating quality of naturally grown teak. In addition, ITTO (2013) reports that the Myanmar Timber Enterprise (MTE), the sole agency responsible for harvesting, extraction and distribution of logs in Myanmar, is drastically reducing its annual harvest volume from native forests.

This situation has led to increased interest and investment in establishing and managing teak plantations. It is more than likely that in the future the world's supply of teak wood will depend on the production of tropical teak plantations. Where good management practices are applied, plantation teak has improved, and there could well be an increasing overlap in quality between natural and plantation-grown teak in future years. Hence, the log export ban in Myanmar has created a market opportunity for international suppliers of plantation teak from Africa and Latin America to expand sales to India and other countries.

In future, small size, fast-grown teak will constitute a significant proportion of the international teak trade and its ready availability and competitive price will see an increase in its use as a timber for general utilities and furniture manufacturing. As such, it is competing with other utility hardwoods such as rubberwood (*Hevea brasiliensis*) and tropical acacias (e.g. *Acacia mangium*), both of which are produced commercially in South East Asia and provide the basis for competitive furniture industries (Midgley *et al.*

2015). In this context, Indian importers have urged plantation teak suppliers to improve plantation tending and management techniques to produce logs of similar quality to those from natural forests (ITTO, 16-30 June 2014).

It can be expected in the future that the sustained production of teak logs from natural forests will be in a continuous decline due to increasing deforestation, strategic considerations of the producer countries and the growing competition for environmental services. Hence, if the genetic resources of natural teak are to be sustained, it appears imperative to organize and implement a global support program for the conservation of natural teak forests.

7.1.3 Markets and Trade[23]

7.1.3.1 Industrial Roundwood

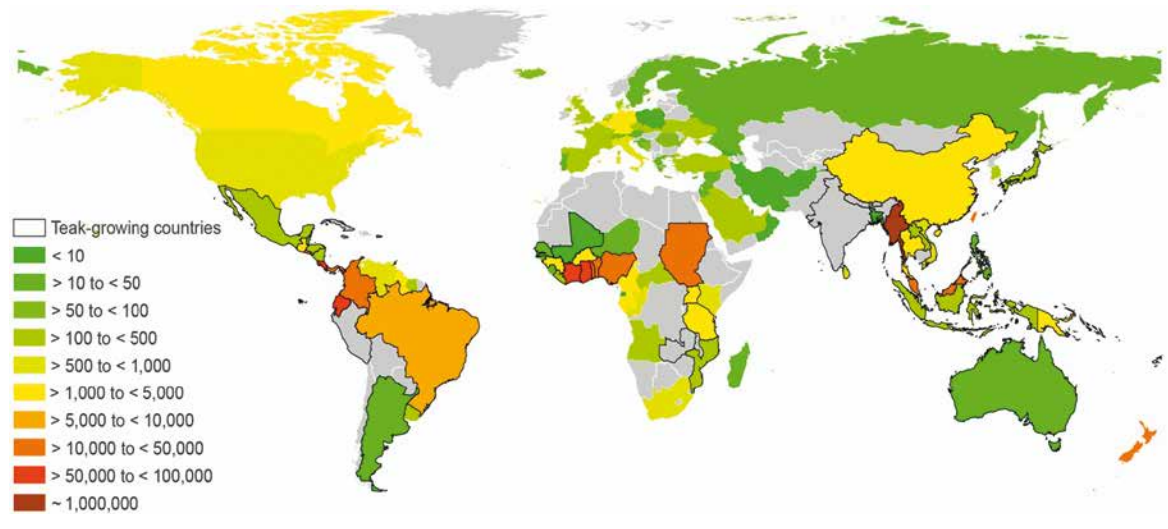
Figure 2 provides an overview of the global trade in industrial roundwood from the perspective of teak-exporting countries: those that grow teak are marked by a thin black line along the border; those coloured red are major teak exporters; while those in yellow and green trade minor volumes. It is worth noting that many industrialized countries in the northern hemisphere (for example Canada, the USA and European countries) that do not grow teak act as vendors of teak roundwood and export considerable volumes to other countries.[24]

FAO's database on forest products statistics (FAOSTAT, http://faostat3.fao.org/home/E) reports the global trade volume of tropical industrial roundwood in the past 10 years at about 15 million m^3 a year on average. The global trade of industrial teak roundwood was found to be slightly more than 1 million m^3, which corresponds to about 7 per cent of the total trade volume (FAOSTAT and Global Trade Atlas). The global demand for teak is expected to grow at a high rate. Factors contributing to growing demand for planted teak include the inability of native teak supplies to meet the demand; rising incomes and domestic demand in major client countries such as India and China.

Between 2005 and 2014, the global annual trade of teak roundwood was more than 1 million m^3 on average; the imports were valued at US$ 487 million a year, which is about 3 per cent of the value of the global timber trade (US$ 15.5 billion). The global teak trade is dominated by three major importing countries: India, which imports three quarters (74 per cent) of the total trade volume of teak roundwood from more than 100 countries; followed by Thailand (16 per cent of the total from about 15 countries) and China (10 per cent of the total from about 65 countries). In terms of import value, India's dominance is even more pronounced, accounting for almost 80 per cent of the global teak trade. Teak imports to Thailand have considerably decreased in

Figure 2

Teak-growing and roundwood-exporting countries



Colours indicate roundwood export volumes, 2005-2014, average in m^3/year; no country was found to be in the 100 000-1 000 000 m^3 range.

[23] The data and information provided are based on national customs data published in the Global Trade Atlas by the Global Trade Information Services (GTIS, www.gtis.com) according to the product identification codes of the Harmonized Commodity Description and Coding System (in brief, the Harmonized System, or HS).

[24] In most industrialised countries, the trade of teak roundwood is recorded in the Harmonized System under "other tropical wood" (code 440349), therefore the exact teak trade volumes of these countries cannot be ascertained. This does not, however, invalidate the observation of teak re-exports from these countries.

recent years, from a peak of 6.7 million m^3 in 2004 to only 61 000 m^3 in 2014. China and India, on the other hand, have shown a marked increase in demand which makes these two the main importing countries.

Since 2000, the global trade in teak logs of the three major importing countries has more than doubled in terms of volume (from 557 000 m^3 to 1.2 million m^3 in 2014), and more than quadrupled in terms of value (from US$ 166 million to US$ 696 million). This increase was mainly borne by India and China. While imports from Myanmar also increased by 27 percent during the observed period, the country's exports could not keep pace with the rising global demand. Consequently, the significance of Myanmar as a global player in the teak trade declined.

Myanmar and its major trading partners, in particular India and China, traditionally play a significant role in the global teak trade. 'Burmese teak' sets international standards for quality, and Myanmar was traditionally the world's largest supplier of teak logs and sawnwood, a supply largely maintained through harvesting of native forests. However, from 1st April 2014, Myanmar implemented a log export ban that has remarkably reduced the availability of mature teak to global markets. In India and Thailand native teak forests grow mainly in protected reserves, so the remainder of global teak wood production, all plantation-grown resources, is accounted for by growers in other Asian countries (notably Indonesia), Africa, and Central and South America.

The log export ban in Myanmar has had a distinct impact on the Chinese market, which imports 80 per cent of its teak from Myanmar. It triggered a rapid increase in the demand for high-quality logs, coupled with a sharp rise in teak prices from about US$ 750/m^3 at the end of 2013 to almost US$ 2 000/m^3 in January 2014.

In India teak is a well-known and preferred species with demand sustained by a boom in construction of residential housing, particularly for doors and windows, wooden furniture manufacturing and economic growth (ITTO, 2010). The increase in Indian demand has been met largely by plantation teak from Central and South America. India's import preference is for round or squared logs, rather than sawnwood, which takes advantage of India's modern infrastructure of ports, low costs of processing and attractively low tariffs for round and squared logs (Midgley *et al.*, 2015).

Katwal (2005) acknowledged that the demand for teak in India has increased several-fold during the past five decades. This strong in-country demand makes India the biggest consumer of plantation grown teak in the world and a downturn in the Indian market would result in a drastic impact on the total market for small-dimension teak worldwide (Somaiya, 2005).

China is the world's largest importer of wood. The total value of China's forest trade exceeded US$ 118 billion in 2012, with exports accounting for US$ 58 billion and imports US$ 60 billion. Although imports of teak logs to China are only 10% of those imported by India, China has a strong demand for sawn teak timber, worth some US$ 41 million in 2012. Chinese imports of both teak logs and sawn timber are increasing. In contrast to India, where teak is used mainly for building, China uses teak predominantly for manufacturing wooden furniture for export.

In terms of value, teak roundwood trade accounts for 12 per cent of the global annual tropical timber trade (US$ 487 million of about US$ 4 billion a year on average between 2005 and 2014), which has slightly increased in recent years. In 2013, the global imports of teak roundwood were valued at about US$ 720 million, while the total import value of tropical industrial roundwood was reported at about US$ 5.4 billion, equivalent to a share of 13.4 per cent (FAOSTAT and Global Trade Atlas).

The market competition from Africa and Latin America has to some extent affected the traditional producers of teak from natural forests in Myanmar, who have lost Indian customers to new market entrants (TEAKNET, 1998). The high international demand for general utility teak has broadened the traditional teak supply base from natural forests in Asia to include fast-grown, small-diameter plantation logs from Africa and Latin America. The emerging teak roundwood traders in Africa are Ghana, Côte d'Ivoire, Benin, Togo, Nigeria and Tanzania (for sawnwood). Latin America, Ecuador, Costa Rica, Panama, Colombia and Brazil (for sawnwood) have continuously expanded their trade volumes since 2000, reaching a peak in recent years, and this trend is likely to continue.

Only a few countries in Africa and Latin America process teak logs to semi-finished or finished products prior to export. Most traders tend to export roundwood to feed the Indian demand for teak. In India, local wood processing mills apply artisanal manufacturing procedures, work at lower costs, and are technically and organizationally well-suited to working with small-diameter logs. Under these circumstances teak growers in Latin America claim that the export of teak to India as roundwood yields a higher return than the processing to and export of finished or semi-finished products (Camacho, 2011).

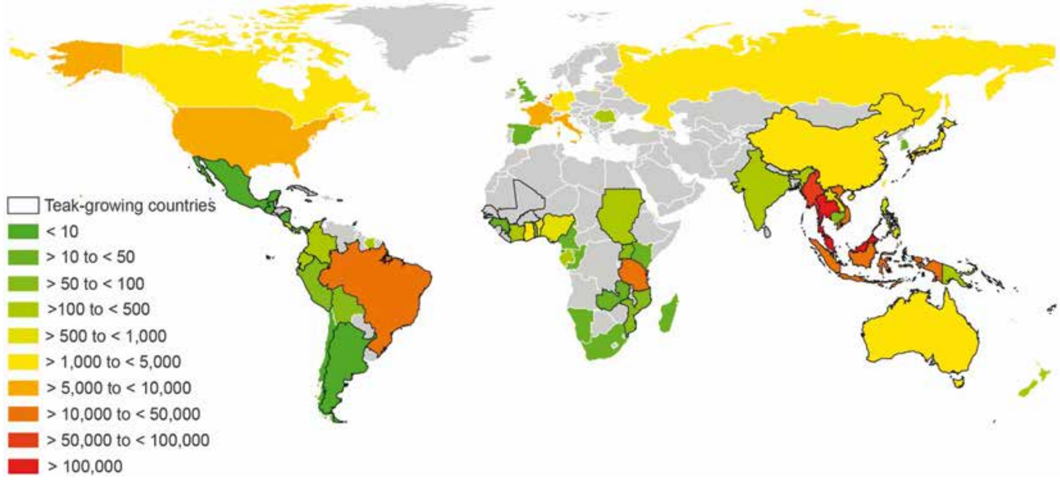
7.1.3.2 Sawnwood

Figure 3 provides an overview of the global trade in teak sawnwood from the perspective of teak-exporting countries: those that grow teak are marked by a thin black line along the border; those coloured red are major teak sawnwood exporters; while countries in yellow and green trade minor volumes. It is worth noting that many industrialised countries in the northern hemisphere (for example Canada, the USA, the Russian Federation and European countries) that do not grow teak act as vendors of roundwood and export considerable volumes to other countries[25].

[25] In most industrialised countries, the trade of teak sawnwood is recorded in the HS under "other tropical wood" (code 440729). Therefore, the exact teak trade volumes of these countries cannot be ascertained. This does not, however, invalidate the observation of teak re-exports from these countries.

Figure 3

Teak growing and sawnwood exporting countries



Colours indicate the sawnwood export volume from 2005 to 2014; average in m^3/year.

From 2005 to 2014, the average annual global trade of teak sawnwood stood at about 120 000 m^3, or about US$ 75 million. It was dominated by five major importing countries: China (accounting for 46 per cent of the total), India (31 per cent), Thailand (14 per cent), Taiwan (7 per cent) and South Korea (2 per cent). While Myanmar's focus in the international teak trade had been on roundwood in the past, sawnwood exports from this country supplied on average half of the total teak sawnwood trade (74 000 m^3, or 49 per cent). However, volumes varied significantly between countries; China and Thailand, for example, imported more than 70 per cent of their teak sawnwood from Myanmar, while the country only supplied 2 per cent of India's sawnwood. In the future, Myanmar's significance in the international sawnwood trade is likely to increase. The log export ban in force since April 2014 was imposed to gain greater control over the international timber trade and promote the export of more semi-finished and finished products. However, the countries that will compete with Myanmar in the global trade of teak sawnwood are predominantly from Africa, where exports have increased since 2008, and from Latin America, where they have risen dramatically since 2010. The emerging exporters are Tanzania (2014: 18 000 m^3) and Benin (2014: 9 000 m^3) in Africa, and Brazil (2014: 10 000 m^3) and Costa Rica (2014: 1 000 m^3) in Latin America.

7.1.4 Volume and Price

Much information on teak prices, in particular from short-rotation plantations, is found in the literature and on the internet, but it is rather difficult to interpret it due to a lack of background information and necessary detail. Available teak prices are mostly based on a case-by-case basis and correspond to a mix of heterogeneous material from different countries that represent wood harvested from planted forests with different silvicultural treatments and timber quality (Coillte Consult, 2006). Some of these data qualify as wishful thinking rather than a reflection of actual values. For this reason much controversy has been generated in several countries by the promotion of teak plantation investments based on fabulous growth and yield projections and unrealistic pricing scenarios, which have provided opportunities to exaggerate rates of return and deceive even cautious investors (Pandey and Brown, 2000, De Camino and Morales, 2013).

The lack of standards and consistency in establishing prices for teak logs has long been a common theme of discussions in international teak markets. Several experts have reflected upon this issue and concur that the creation of uniform international log grades for plantation teak, along with standardized lumber and product grades would be of great help to improving the marketability of teak wood products as buyers would know the exact quality of the products being offered for sale (Keogh, 2007; Moya and Pérez, 2008; Ladrach, 2009).

As a general rule it can be established that teak prices are very closely related to size and quality. Considerably higher prices are being paid for large, long rotation (>50 years), slow-grown teak, usually produced in native forests and plantations from Indonesia, West Africa and Trinidad and Tobago. Quality in teak is determined by dimension, bole shape (roundness and straightness), heartwood/sapwood ratio, regularity of annual rings, number of knots, colour, texture and the soundness of the butt log. Teak from natural forests in general possesses many of these features to some extent and sells at comparatively high prices. Logs from planted teak forests are typically smaller in size and will hardly ever reach the dimension, quality features and prices of logs grown in old-growth forests. In addition, badly managed plantations or teak plantings on poor sites often exhibit heart rot at ground level, negatively affecting the most valuable segment of the tree. Many of these factors are linked with age and tree size. The standard range of products obtainable from planted teak forests that are harvested at young age are short boards, scantlings and mouldings. They will be 5 to 15 cm in width and up to 3 m in length, and most of them have a distinct colour pattern marked by the dark-brown core and the yellowish sapwood. But they are very suitable for the manufacture of furniture, parquet flooring, picture frames, boat parts, gift items and carvings (Midgley *et al.*, 2015).

As a consequence of the scarcity of good quality teak, prices of roundwood are expected to have increased in the past. From 2005 to 2014, the prices of quality teak logs from Myanmar and plantation teak logs from Africa and Latin America showed an upward trend of 3-4.5 per cent a year on average. However, the markets and prices for these products are fundamentally different. The unit price of quality teak logs imported from Myanmar is higher than those for imports from other countries, notably in the Indian market. Here, the unit price of teak logs from Myanmar started at US$ 615/m^3 in 2005 and reached a peak of almost US$ 1 000/m^3 in 2014. Imports from Africa and Latin America showed a much slower increase, from about US$ 320/m^3 to US$ 430/m^3 in the same period.

Increasingly important considerations influencing global teak wood markets include sustainability, certification and the legality of logs. The markets of North America and Europe have responded legislatively through the Lacey Act (USA) and the European Union Timber Regulations (EUTR). Governments, buyers and retailers, mainly in western countries have embraced the principles of certification, seeking reassurances of sustainability and environmentally responsible production (Midgley *et al.*, 2015). Legality is not an issue in all markets, however. Although India represents three-quarters of the global market, most of its production of teak products is for domestic consumption. At present, the Indian domestic market is generally unresponsive to legal verification or certification, and thus is unwilling to pay for these additional costs.

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7.2 Financial Appraisal of Planted Teak Forest Investments

Hugh Brown[26] and Walter Kollert[27]

7.2.1 Summary of Assumptions and Results (see Box 1)

Box 1

Land Area: 125 ha
Effective Teak Plantation Area: 100 ha
Cost per man-day: US$ 5
Initial Spacing: 3m x 3m
Rotation: 25 years
Cost per hectare (over 25 years): US$ 8, 420
Revenue per hectare (over 25 years): US$ 44, 250
Net Present Value (NPV): US$ 364,091
Internal Rate of Return (IRR): 16%

7.2.2 Introduction

7.2.2.1 Teak in Ghana

Teak is reported to have been introduced into Ghana (then Gold Coast) from Myanmar (then Burma) in 1905 and planting trials were undertaken in the Volta Region (Kadambi, 1972). However, the establishment of commercial plantations of teak only commenced around the late 1940s primarily in the Volta Region and later spread to other parts of the country such as the Ashanti, Brong Ahafo and Eastern Regions. Since the 1960s large areas of teak plantations have been established under government programs within degraded forest reserves and more recently by the private sector within off-reserve areas and degraded forest reserves especially in the dry semi-deciduous forest zone.

The total area of teak plantations in Ghana is currently estimated at 180,000 ha with the species being planted in all ten regions of Ghana with a high concentration within the middle belt (Ashanti and Brong-Ahafo regions). Of this total figure, public owned plantations are estimated to cover 107,000 ha (60%) while the remaining 73,000 ha (40%) are owned by the private sector. Approximately 50% of the private sector teak estate are smallholder plantations (< 4ha) and small-scale commercial plantations (4-100 ha), 30% are medium-scale commercial plantations (101-1000 ha) while the remaining 20% are large-scale commercial plantations (1000+ ha). The large-scale commercial forest plantations are owned mainly by three companies: Form Ghana Limited, Miro Forestry (Ghana) Limited and Mere Plantations Limited. These establishments are located within degraded forest reserves and are being developed in partnership with the Forestry Commission. Most of the publicly owned plantations fall within the small and medium scale commercial plantation category (Figure 1).

The predominant initial spacing used is 3m x 3m with three or four thinning operations prior to final harvest. Current rotation ranges from 20 to 25 years.

Most of the teak produced from commercial thinning operations and harvesting from private and public owned plantations is exported as logs (billets and poles) and lumber. The Indian market is the major destination of these products which are usually containerized (20-footer containers) and exported by sea. There is, however, a thriving local market for teak poles from thinning operations for use as treated wooden poles for telegraphic transmission and low and high-tension electricity transmission. Saw logs are also used locally by the furniture and joinery industry.

7.2.1.2 Financial Appraisal – Definition

Financial appraisal is a method used to evaluate the viability of a proposed project by assessing the value of net cash flows that result from its implementation. It views investment decisions from the perspective of the investor/firm. It considers whether the projected revenues will be sufficient to cover expenditures and whether the

Figure 1

5-month old teak plantation established by Mere Plantations Ltd. in partnership with the Forestry Commission within the Afram Headwaters Forest Reserve, Ghana. Photo © H. Brown

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Table 1

Summary investment cost (year 1 -25) for a 100 ha commercial teak plantation

ACTIVITY/OPERATION	COST (US $)	COST (US $/ha)
Land Rent	15,625.00	156.25
Survey, Demarcation & Mapping	3,000.00	30.00
Project Documentation	10,000.00	100.00
Seedling Procurement	33,250.00	332.50
Establishment (Site preparation, planting, etc.)	44,250.00	442.50
Plantation Maintenance / Tending	351,000.00	3,510.00
Human Resource (Supervision & Management)	270,000.00	2,700.00
Machinery / Capital Inputs	29,470.00	294.70
Running and Maintenance Cost of Vehicle (Pick Up Truck)	85,400.00	854.00
TOTAL	**841,995.00**	**8,419.95**

financial return will be sufficient to make the investment commercially viable (profitable).

Due to the long-term nature of forest plantation investments the Net Present Value (NPV) and Internal Rate of Return (IRR), both of which utilise analyses of discounted cash flows, will be employed in this report to analyse the profitability of teak plantation investments.

7.2.2 Investment Costs

The cost of establishing, maintaining and managing a 100 ha teak plantation over a 25-yr period is summarised in Table 1.

7.2.2.1 Pre-Establishment Costs

Pre-establishment investment costs usually cover land acquisition/rental fees, survey and demarcation, layout planning, preparation of project documents/plans, tree nursery costs or cost of procuring seedlings/stumps, etc.

7.2.2.2 Establishment and Maintenance

For the purpose of this analysis a 100 ha teak plantation on a 125 ha estate (equivalent to 1 Forest Reserve compartment) was modeled. As a standard, 25 hectares were assigned to strips of protected forest around ecologically sensitive areas within the estate in which no operations take place apart from roads/rides and other plantation infrastructure and no revenue is expected but costs will be incurred. Establishment costs include construction of fire strips/roads, site preparation, peg cutting, lining and pegging and planting out. The assumed planting density is 1100 seedlings/ha, a standard widely applied in Ghana.

Post-planting maintenance operations include weeding/weed control, singling, pruning, etc.

7.2.2.3 Logging and Harvesting Costs

Based on the adopted thinning regime there will be four thinning operations (Years 5, 10, 15, and 20, Figure 2) prior to final harvest in year 25. The first thinning (Year 5) is considered non-commercial. For the purpose of this analysis standing tree values are used instead of log or processed lumber values. Currently most teak from Ghana is exported as billets (short logs of approximately 8ft [2.4m] in length). The harvested logs are crosscut into billets and packed into 20-foot containers for export, usually an average of 13.5 m^3 per container. In some cases the billets are squared to enable more efficient utilization of container space and this allows between 18-22 m^3 of squared lumber per 20-foot container, depending on size, the quality of milling and expertise of loaders. Estimated average logging and harvesting costs (including loading

Figure 2

Thinning operation within a 14-yr old teak plantation established by Form Ghana in partnership with the Forestry Commission within the Asubima Forest Reserve, Ghana. Photo © H. Brown

Table 2

Revenue from a 100 ha large commercial teak plantation over a 25-yr rotation

YEAR	USE/TYPE OF PRODUCTS	UNIT PRICE/TREE (US$/tree)	UNIT PRICE/ m³	QUANTITY/ 100 ha	INCOME/ 100 ha	REMARKS
5	Posts					Estimated 350 trees removed per hectare (sanitary thinning) leaving 750 trees per hectare. Pre-commercial
10	Telegraphic / low tension electricity transmission poles	US$ 25	US$ 166	25,000	US$ 625,000	250 trees removed per ha. First commercial thinning. (Estimated 0.15m³ merchantable volume per tree)
15	High tension electricity transmission poles/saw logs	US$ 45	US$ 180	15,000	US$ 675,000	150 poles per ha. – Second commercial thinning (estimated 0.25m³ merchantable volume per tree)
20	Saw logs	US$ 75	US$ 214	15,000	US$ 1,125,000	150 trees/saw logs per ha. – Third commercial thinning (estimated 0.35m³ merchantable volume per tree)
25	Saw logs	US$ 100	US$ 250	20,000	US$ 2,000,000	200 saw logs per ha. – Harvest (estimated 0.40m³ merchantable volume per tree)
TOTAL					US$ 4,425,000	

& transportation to port), certificates and port charges are estimated to range between US$100 and US$150 per cubic meter of logs/billet depending mainly on log sizes, logging and harvesting efficiency and distance to port. Where squared lumber is exported, the average costs (including processing) are estimated to range between US$ 120 and US$ 180 per cubic meter.

7.2.3 Expected Revenue

Revenue is expected from commercial thinning operations (Year 10, 15, 20) and the final harvest in year 25. A total revenue of US$ 4,425,000 (standing tree value) is expected from the 100 ha teak plantation over the 25-yr rotation. Table 2 summarises revenue flows over the period. Expected revenue forecasts under this study are based on current stumpage prices of teak in Ghana.

7.2.4 Data Quality

Growth and volume estimates used are based on average actual inventory data of the last 10 years within Forestry Commission (FC) plantations and recent data from private operators such as Form Ghana. Merchantable volume of standing timber is determined by applying appropriate artificial form factors to utilisable height and

Financial appraisal of a 100 ha teak plantation (25-yr rotation) Table 3

YEAR	EXPENDITURE (US$)	REVENUE (US$)	NET CASH FLOW (US$)	CUMULATIVE CASH FLOW (US$)
1	151,905.00		(151,905.00)	(151,905.00)
2	41,485.00		(41,485.00)	(193,390.00)
3	40,005.00		(40,005.00)	(233,395.00)
4	38,845.00		(38,845.00)	(272,240.00)
5	48,845.00		(48,845.00)	(321,085.00)
6	42,345.00		(42,345.00)	(363,430.00)
7	42,345.00		(42,345.00)	(405,775.00)
8	29,845.00		(29,845.00)	(435,620.00)
9	29,845.00		(29,845.00)	(465,465.00)
10	42,345.00	625,000.00	582,655.00	117,190.00
11	28,685.00		(28,685.00)	88,505.00
12	40,785.00		(40,785.00)	47,720.00
13	27,805.00		(27,805.00)	19,915.00
14	40,305.00		(40,305.00)	(20,390.00)
15	27,805.00	675,000.00	647,195.00	626,805.00
16	32,325.00		(32,325.00)	594,480.00
17	19,825.00		(19,825.00)	574,655.00
18	19,825.00		(19,825.00)	554,830.00
19	19,825.00		(19,825.00)	535,005.00
20	19,825.00	1,125,000.00	1,105,175.00	1,640,180.00
21	11,955.00		(11,955.00)	1,628,225.00
22	11,305.00		(11,305.00)	1,616,920.00
23	11,305.00		(11,305.00)	1,605,615.00
24	11,305.00		(11,305.00)	1,594,310.00
25	11,305.00	2,000,000.00	1,988,695.00	3,583,005.00
TOTAL	**841,995.00**	**4,425,000.00**	**3,583,005.00**	

IRR = 16%, NPV (10%) = US$ 364,091

diameter (dbh) measurements. Though the average cost per man-day currently ranges between US$ 3 and US$ 4, this study used a rate of US$ 5 to reflect the steady but gradual increase in real cost of labour since Ghana attained lower middle-income status about 9 years ago.

7.2.5 Financial Analyses

7.2.5.1 Net Present Value (NPV)

In finance, the net present value (NPV) is a measurement of the profitability of an undertaking that is calculated by subtracting the present values (PV) of cash outflows (including initial cost) from the present values of cash inflows (income) over a period of time (Kurt, 2003). NPV is used in capital budgeting to analyse the profitability of a projected investment or project.

The rate used to discount future cash flows to the present value is a key variable of this process. A firm's weighted average cost of capital (WACC) after tax is often used, but in practice analysts usually use higher discount rates to adjust for risk, opportunity cost, or other preferences. For the purpose of this study a discount rate of 10% is used for the NPV analysis. This is the conventional World Bank discount rate for analysing long-term investments, which is considered rather high by many financial analysts for the evaluation of natural resources (Tawari and Chanduvi, 2013; Markandya and Pearce, 1998; Baneth, 1996), but due to the relatively high commercial interest rate in Ghana (7.5-11% on the US Dollar) the rate of 10% is considered a fair estimate.

The NPV of the investment is US$ 364,091 at a cost of capital of 10% (Table 3).

7.2.5.2 Internal Rate of Return (IRR)

The internal rate of return on an investment or project is the "annualized effective compounded return rate" or rate of return that makes the net present value of all cash flows (both positive and negative) from a particular investment equal to zero or, in other words, the rate at which an investment breaks even. IRR is used in capital budgeting to measure and compare the profitability of investments. The NPV formula is used to calculate IRR by equating NPV to zero and solving for "r".

The Internal Rate of Return of the investment is 16% (Table 3). It is expected that with larger establishments (500 ha +) significant economies of scale will be achieved leading to higher rates of return (i.e., 18 - 22%).

7.2.5.3 Sensitivity Analysis

Uncertainty is a dominant feature of all projects, especially if they are long-term. One way to treat risks is by adding a premium to the discount rate to reflect risk and uncertainty of the investment and to determine whether the project still yields a positive NPV or an acceptable rate of return. In this particular case by using a relatively high cost of capital (10%) and still coming up with a positive NPV (US$ 364,091) the outcome shows how robust the investment is. Further analyses were conducted by increasing annual expenditure by 20% while the revenue stayed the same and yet a positive NPV (US$ 270,948) with an IRR of 14% was realised. Revenue forecasts were reduced by 20% (or 20% reduction in timber yields/volume) and yet a positive NPV (US$ 198,130) with an IRR of 14% was realized. The final scenario was a reduction of 20% of revenue together with an increase of 20% in project costs/expenditure and yet again a positive NPV (US$ 104,987) with an IRR of 12% was achieved. The best way to mitigate risks is to actually anticipate them and build adequate mitigation measures within the project framework. In this model, for example, the risk of fire is addressed in the project framework by constructing fire rides and undertaking fire patrols, which ensures that fires are prevented or in case they occur, there is early detection which makes suppression relatively easy.

7.2.6 Conclusions

The results of this study compare favourably with teak investments of similar scale in Ghana. In the case of large-scale private teak plantation developers in Ghana such as Form Ghana, Miro Forestry Company Ltd. and Mere Plantations Ltd., projected returns (IRR) are higher (18-24%), mainly due to considerable economies of scale and cost-reduction management interventions such as encouraging intercropping of plantation area with food crops by nearby farming communities, which leads to lower cost of weeding on the part of the company. Additionally, these companies raise their own seedlings, which, apart from giving them control over the quality of planting material, also leads to lower unit costs. It is evident from the analysis that teak investments when undertaken under the right climatic and edaphic conditions that promote good growth, with good genetically superior planting material, yield attractive and robust financial returns to the investor, provided that good management and appropriate silvicultural practices are applied.

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7.3 Long-term Price Trends of Teak Wood

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7.3.1 Introduction

In their latest teak resources and market assessment Kollert and Cherubini (2012) state that the declining supply from natural teak forests may produce advantages for the long-term prospects for plantation-grown teak. They conclude that demand and consequently prices are likely to increase. Reliable information on teak prices, in particular from short-rotation plantations, is scarce and available data are difficult to interpret and do not readily allow for comparisons. Grades (quality), processing type (sawn, mouldings, dried, round wood), market location (stumpage value, country ex-forest road, ex-mill), and trade status (FOB, CIF) are in-transparent, hardly published and make judgements difficult. Economic appraisals of afforestation projects, which are needed for satisfying the increasing wood demand are consequently rather unreliable.

On the other hand, teak forests are often target of private investments and managers attract clients with optimistic returns, which are largely based on assumed timber price increases. To that end, independent and long-term timber price data are essential for market transparency and appropriate risk-return assessments.

7.3.2 Material and Method

The analyses and findings in this paper are based on publicly available time-series for tropical timber prices published by the International Tropical Timber Organization (ITTO). Fortnightly reported timber prices by country and species have been published since 1998 in the Tropical Timber Market Report (ITTO, 1998-2016). Regarding data for teak, only prices of teak logs from Myanmar were published in 1998. Since July 2009, prices of plantation-grown teak have been included. The compilation of these data allowed the development of price-indices to monitor tendencies and relevant dependencies of the teak price development.
We developed various indices for several purposes:

1. Index for species for planted forests, which includes Eucalypts, Pine, and Rubber wood (*Hevea brasiliensis*);

2. Index for natural forest species, which includes Teak, Meranti (*Shorea* spp.), Selangan Batu (*Shorea* spp.), Ipé (*Handroanthus* spp.), Jatoba (*Hymaenea courbaril*), and Khaya (*Khaya ivorensis*);

3. Index for natural teak round wood, which includes one grade from Myanmar;

4. Index for planted teak, which is based on three grades for sawn wood, delivered to the domestic Indian market.

For indices 1, 2 and 3, we are using the cubic meter related prices in USD in 1998 and set them to index level of 100. For index 4, we also apply cubic meter related prices in USD, however, since data for plantation grown teak are only available after July 2009, we set the index reference to 100 for this year (2009). In order to be able to compare teak only, we have also recalculated index 3 with the reference level set at 100 for 2009. Index 4 was developed from a mix of different grades of domestic sawn wood prices for plantation teak in India. Plantation-grown teak export prices are only reported very occasionally from exporting countries and mostly without quality references. India is the major importing teak round wood country in the world (Kollert & Walotek, 2015), and also an important teak sawn timber importer. We consider our index 4 therefore meaningful for world market tendencies. Imported plantation wood in India represents a mix from different origins, which changes every year and available prices are only related to the total imported volume, also without quality references. We assumed that domestic sawn wood prices represent market related tendencies for imported plantation teak, as they are directly linked to the available supply and demand.

For all market analyses, we used the Pearson correlation coefficient, as it contains a correction around the average values and a scaling on the standard deviation. The Pearson coefficient can achieve a maximal value of 1.0, indicating the best correlation, while value 0 confirms that no correlation exists. Negative correlations between 0 and -1 are describing inverse situations. Correlations can be computed for any time window.

Other commodities were treated similarly to allow relative comparisons. Moreover, we express volatility as standard deviation in relative terms.
In our work we use two timber-price-related dependencies:

a. for **transport costs,** we applied the historical data for the European crude oil type "Brent Spar", which is published by the U.S. Energy Information Administration; and

b. for **market consumption,** we assessed the Indian local market development for house construction. Residential construction is an urban development indicator, which influences timber consumption and thus market prices.

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Price index increase and volatility of selected tropical forest species since 1998

Table 1

	Index 2					Index 3	Index 1			Mean Index
Index Jan 1998 (= 100)	**Meranti**	**Selangan Batu**	**Ipé**	**Jatoba**	**Khaya**	**Teak**	**Eucalyptus**	**Pine**	**Rubber-wood**	**Average**
Index Aug 2014	181	292	213	175	266	249	152	132	184	205
Increase p.a. (%)	3.78	6.93	4.84	3.56	6.31	5.87	2.65	1.75	3.88	4.59
Volatility (%)	47	63	51	51	40	46	31	34	24	43
Index Aug 2016			202	135		310	125	106		176
Increase p.a. (%)			3.98	1.68		6.49	1.25	0.32		3.18
Volatility (%)			53	48		56	38	43		48

Source: ITTO, modified data from Tropical Timber Market Reports, 1998 to 2016.

The Housing Index from India – RESIDEX[30] – is reported by the National Housing Bank. The Indian RESIDEX tracks residential property/real estate prices for major cities in India and indexes them on a certain date. Data are collected by National Housing Bank of India. The Indian RESINDEX is the equivalent to e.g. the "housing starts"[31] in the US. Similarly to the US one, certain dependencies between house construction and timber prices are expected. For India, particularly correlations with the teak prices are expected, as sawn timber consumption is directly related to the house construction market. Teak is a resource for structural, finishing work processes.

7.3.3 Results

Timber Price Indices for Long-Term Periods

The combined price index for tropical timber (i.e., the combination of indices 1 and 2) has increased from 100 in January 1998 to 229 in August 2014. This corresponds to an annual increase of approx. 5.1 percent in nominal terms. Volatility computes to 43 percent. In the same observation period, the teak price index (Index 3) rose from 100 to 249, or approx. 5.9 percent p.a., i.e., 0.8 points higher than the mixed index (Index 2). Volatility of teak was 46 percent and thus similar to the NFS-Index. Overall, teak showed the third largest price increase after Selangan Batu and Khaya. The latter two had the highest growth rate of 6.9 and 6.3 percent p.a., respectively. The lowest price increase of 1.3 percent p.a. applies for Pine.

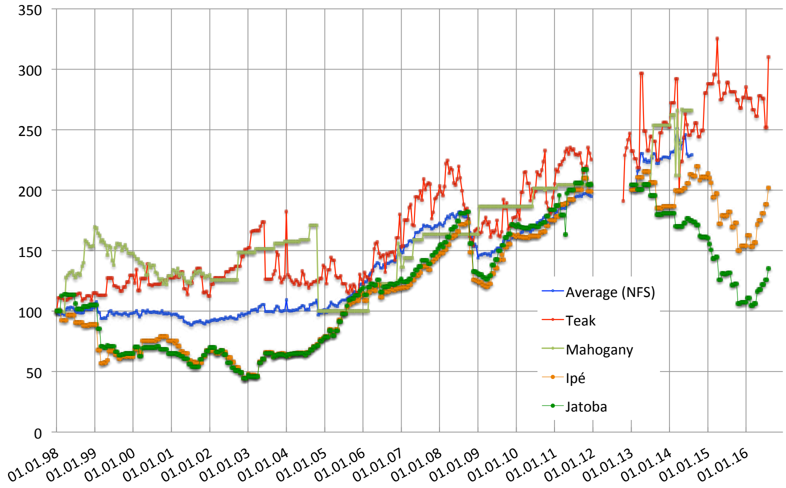
In 2014, price publications by ITTO for some species were discontinued. Thus, it was not possible to continue reporting on Meranti, Selangan Batu, Rubberwood, and Khaya. Discontinuation was partially caused by export bans for grades and/or species. Teak data also suffered from such impacts since the Teak Export ban in Myanmar, as reported by Kollert & Walotek (FAO, 2015). The continuation of the natural teak index was possible due to the reporting of local auction prices for teak round logs, where international market participants were placing their bids.

[30] The India NHB RESIDEX was released in 2007 covering five major cities. Currently the Bank compiles quarterly house price indices for an increasing number of major cities. This index is publicly available with a delay of one year.

[31] http://www.tradingeconomics.com/united-states/housing-starts

Figure 1

Development of teak and mixed species price indices since January 1998.



Source: ITTO, modified data from Tropical Timber Market Reports (1998 to 2016)

Therefore, we provide the development of the teak index and other prominent natural forest species like Ipé and Jatoba. We also report on planted species like Eucalyptus and Pine. As shown in Table 1, the teak price index rose from 249 in 2014 to 310 in August 2016. Related to 1998, this means an annual increase of 6.5% p.a., an even steeper increase than until 2014. However, volatility also increased to 56 %. The export ban of teak from Myanmar resulted in a strong peak of the index. This heavily affected importing countries like India, as reported by Kollert & Walotek (FAO, 2015).

The other observed species do not show the same extreme changes in recent years. Prices remain lower compared to the results of 2014. The Mean Index for natural forest species in 2016 is lower than in 2014 (Table 1, last column).

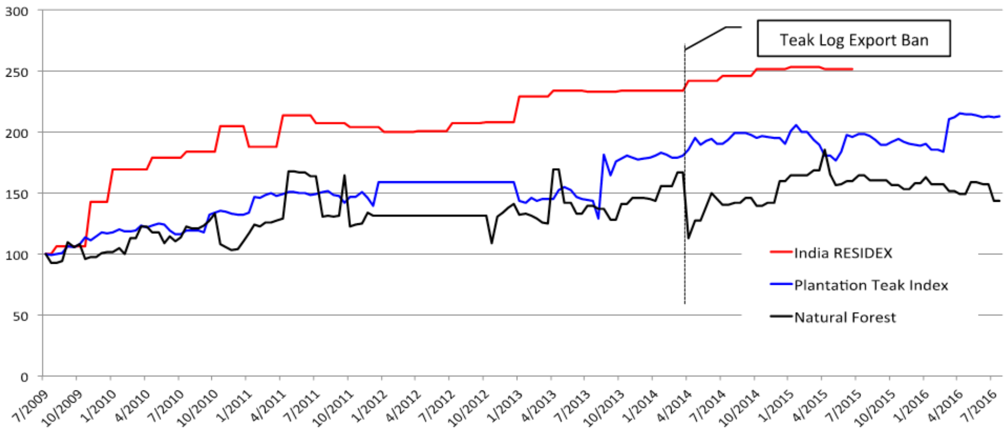
A detailed analysis of the natural forest species (Figure 1) shows that the teak price index (red line) is always superior to the average price index (blue line) for the entire observation period, though fluctuations are quite significant. The average index is made up of a mix of species, which smoothes these fluctuations. The data also display a clear increase of the teak index over the last four years. This tendency is obvious for teak, but not for the other natural species, like Ipé and Jatoba.

Natural Versus Planted Teak

In the following, we analyse the index development for teak only (natural vs. planted). Here, also striking differences can be noted. This comparison is very relevant, as it was not clear if plantation teak prices would follow those of natural teak. We report on the comparison of the last

Figure 2

Tendencies of the natural and plantation teak price indices and the India RESIDEX



Source: ITTO, modified data from Tropical Timber Market Reports (2009 to 2016); National Housing Bank of India, modified data 2007 to 2015.

seven years and would like to underline that a generalization of the price trends is not yet possible as data are insufficient for long term trends derivation. Hence, data should be used as indicators only (Fig. 2).

Table 2 **Average teak price indices in 2016.**

Index Jan 2009 (= 100)	Natural Forest Teak Index Index 3	Plantation Teak Index Index 4
Index Aug 2016	144	213
Increase p.a. (%)	5.35	11.41
Volatility (%)	47	63

Source: ITTO, modified data from Tropical Timber Market Reports, 2009 to 2016.

In the observation period from 2009 to 2016, the price index for natural teak rose from 100 to 144, i.e., 5.4 % p.a. The index for planted teak increased to 213 or 11.4 % p.a., respectively (Table 2). Both indices are weakly correlated with the Indian RESIDEX, which shows an increase by 16.5 % p.a. in the same period.

The natural teak price index experienced a sharp decline after the Teak Export Ban in Myanmar in April 2014 (dashed line), but recuperated to the previous level one year later. The plantation teak price index keeps increasing during this period and was not affected by the ban.

Timber Price Indices in Comparison with Indices of other Markets

The comparison of both teak indices with the India RESIDEX shows positive correlation for the plantation teak price index, and surprisingly mostly negative and weak correlation for the natural teak price index. For natural teak this indicates that practically no correlations with the India RESIDEX exist. The correlation between the India RESIDEX and the plantation teak index is fluctuating between 0.23 and 0.83, as shown in Table 3. It can be observed that the weakest correlation was in the years 2011 and 2012. The global teak trade assessment (Kollert & Walotek, 2015) reported that in 2011 a massive increase of round wood imports from emerging markets to India commenced. Also sawn wood imports reached the highest volume in 2011. This situation probably explains the outlier for the correlation. Imports were possibly flooding the markets and price developments were not reacting as expected.

Further, the correlation of the Indian RESIDEX and the plantation teak index experienced the tightest correlation in 2014, which was the year of the natural teak export ban. Direct dependencies of the events are uncertain. However, we assume that plantation teak prices are closer correlated to the Indian RESIDEX than estimated and our data analysed.

The correlation of the natural teak price index with the Indian RESIDEX fluctuates over time. Prices are probably more related to the restricted market supply than the national demand in India.

In a further step, we also investigated the teak price development in relation to prices for crude oil representing transport costs (see Figure 3). The strongest correlation is found in the period of the extreme oil price increase from January to June 2008. The correlation coefficient in this period is around 0.86. However, in the total observed period of 19 years, there was no clear statistical evidence of a dependency between the Teak Index and Crude Oil Index.

7.3.4 Conclusions

The presented teak price indices are based on price information publicly available in the Tropical Timber Market Report by ITTO, which should only be used for long-term observations after an appropriate standardization procedure has been applied. Teak market prices and their associated indices show certain tendencies and are only weakly correlated to other commodity prices, e.g. oil price.

The natural teak price index increased on a long-term period since 1998 by 5.9 per cent p.a. A comparative

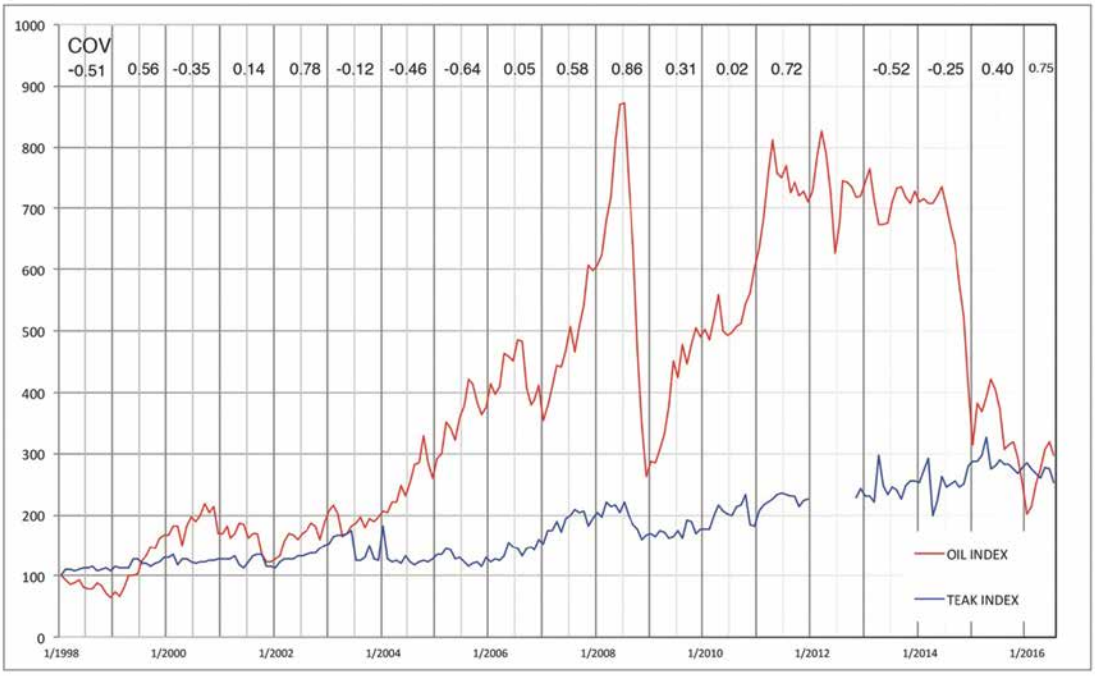
Table 3 **Pearson coefficient (COV) for the correlation between the India RESIDEX and the teak price indices**

Year	2009	2010	2011	2012	2013	2014	2015
COV - RESIDEX and Plantation Teak Index	0.81	0.77	0.35	0.23	0.49	0.83	0.68
COV - RESIDEX and Natural Teak Index	-0.01	-0.21	0.67	-0.04	0.58	-0.27	0.12

Source: ITTO, modified data from Tropical Timber Market Reports, 2009 to 2016; National Housing Bank of India, modified data from 2007 to 2015.

The development of established price indices of oil and teak over a 19 year observation period; the Pearson correlation coefficient COV is given for annual periods.

Figure 3



Source: ITTO, modified data from Tropical Timber Market Reports, 1998 to 2016; U.S. Energy Information Administration, modified data on crude oil prices 1998 to 2016.

analysis of this index with the plantation teak price index was only possible on a shorter period, as available data for plantation teak are only available from 2009. In a direct comparison, the plantation teak price index increased much more (11.4 per cent p.a.) compared to the natural teak price index during the observation period (2009-2015). This might be caused by the low teak supply from natural sources and high teak wood demand, which made the market swerve to plantation teak products. Nevertheless, the absolute cubic meter related prices in USD clearly indicate the superior status of natural teak timber. While the mean local sawn timber price of plantation teak shows a value of 2,892 USD/m^3 (CIF) in August 2016, the natural teak round wood from Myanmar enters our calculation with 3,374 USD/m^3 (ex forest road). If we would convert the natural round wood price roughly to an associated sawn timber price (applying 50% yield + USD 100/m^3 for processing + USD 50/m^3 for transport), the sawn timber price of the natural product is easily double as high as compared to the product from planted forest.

Our analysis doesn't show a clear correlation of teak price indices with the index for crude oil reflecting transport costs, but confirms a dependence of the teak price indices with the house construction (in India). Both teak indices – natural and planted forest – are correlated with the India RESIDEX, an official index created by the National Housing Bank of India that tracks residential property/real estate prices for major cities. We can confirm that the monitoring of the Indian Housing Index allows general predictions on the development of the plantation teak prices. Moreover, our analysis suggests that the development of the crude oil price reflecting transport costs can have an impact on the natural teak prices. However, a prediction of the development of teak prices from the oil price index is not possible.

7.3.5 References and Further Reading

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